Synthesis and Characterization of Cu-graphite-SiC Hybrid Metal Matrix Composite Prepared by Powder Metallurgy Route

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Technology
in
Metallurgical and Materials Engineering

by

Arabinda Meher

Department of Metallurgical and Materials Engineering
National Institute of Technology Rourkela
Rourkela, Orissa-769008, India

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(213MM1472)

Under the supervision of

Prof. Debasis Chaira

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National Institute of Technology Rourkela
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CERTIFICATE

This is to certify that the thesis entitled, "**Synthesis and characterization of Cu-graphite-SiC hybrid metal matrix composite prepared by powder metallurgy route**", submitted by **Arabinda Meher (213MM1472)** in partial fulfilment of the requirement for the award of **Master of Technology** degree in **Metallurgical and Materials Engineering** at **National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date: 28th May 2015

Prof. D. Chaira
Department of Metallurgical and Materials Engg.
National Institute of Technology, Rourkela – 769008

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Arabinda Meher

arabinda147@gmail.com

Abstract

Copper based hybrid metal matrix composites reinforced with graphite and SiC by powder metallurgy route takes the advantage of both graphite and SiC. Graphite helps in improving the wear resistance as graphite acts as a lubricating film on the contact surface and its having small co-efficient of thermal expansion, but hardness decreases due to softness of graphite. SiC helps in improving the hardness of the composite. Copper based hybrid metal matrix composites are used in many electrical contact applications like contact bushes and bearing materials. Cu based metal matrix composite is also used as heat sink because of its low co-efficient of thermal expansion and packaging of microelectronics compact. In our present investigation, attempts have been made to fabricate Copper–graphite-SiC hybrid metal matrix composites by powder metallurgy route. The main aim is to improve the mechanical properties and wear resistance of composite with a minor loss of electrical conductivity.

Cu-graphite-SiC hybrid metal matrix composites were fabricated using copper powder reinforced with 1, 3, 5, 10 and 15 vol. % graphite along with 2, 5, 10 wt. % of SiC. Powders were blended in a turbula shaker mixer for 30 minutes. The composite powders were cold compacted by uni-axial pressing upon applying a pressure of 700 MPa for 5 minutes. The compacted samples were sintered in a tubular furnace at 900^{o}C for 1h in argon atmosphere. For comparison, coarse and fine SiC powders were used to study the effect of SiC particle size on the mechanical and electrical conductivity of the fabricated composites. X-ray diffraction (XRD) was used to identify the phases of the composite. Microstructural analysis was carried under optical microscope, SEM (Scanning electron microscope) and FESEM (Field emission SEM), which shows the uniform distribution and good bonding of graphite and SiC reinforcement with copper matrix. Archimedes' principle was used to determine the relative density of the composites and it was found that relative density increased from 78.0 to 86.5% with increase in the amount of reinforcement for coarse SiC particle. For fine SiC particle, the value of relative density was found around 88.5%. It was observed that hardness of the composites increased with increase in SiC content and it decreased with increase in graphite content. The maximum hardness value was achieved for high content of SiC and low content of graphite as the maximum hardness value of 76.1 VHN for Cu-1 vol. % graphite-10 wt. % SiC whereas for pure Cu hardness value was 32 VHN. It was noticed that hardness of the composites containing fine SiC particle is more as compared to coarse SiC particle. Compressive strength of the composites decreases with increase in the graphite content.

There was an increase in compressive strength with addition of higher amount of SiC for fixed content of graphite. Compressive strength of the composite containing fine SiC particle is more as compared to coarse SiC particle. Non-lubricated sliding wear resistance of the composite increases by addition of graphite and SiC in the hybrid composite as graphite act as lubricating film on contact surface and addition of SiC support the stress on the contact surface which prevent plastic deformation but abrasion takes place on the surface. Electrical conductivity of the composites decreased with the increase in the amount of graphite and SiC. The electrical conductivity value for pure Cu was found to be 4.39×10^6 Siemens/m and it decreased to 1.93×10^6 Siemens/m for Cu-15 vol. % graphite-10 wt. % SiC. Electrical conductivity of the composite containing fine SiC particle is lower than coarse SiC.

***Keywords*:** Hybrid metal matrix composite; powder metallurgy; microstructural analysis; hardness; wear resistance; compressive strength; electrical conductivity.

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Chapter 1
Introduction

1. Introduction

1.1 Background and motivation

In the modern era require unusual combination to get the desired properties of the material by the combination of two or more different materials. Metal matrix composite provide a novel way of strengthening of material. Over the last decade attempts has been made to reinforcing the metal or alloy with other ceramic based reinforcing material by liquid and solid phase bonding to get the optimum properties of the materials. Solid phase bonding is generally done by the powder metallurgy route where compaction and sintering is done to get the pores free and dense products [1]. Metal matrix composite gives both metallic properties like high toughness and ductility as well as ceramic properties like high strength and modulus. Metal matrix composites consist of a family of discontinuous reinforcement either it may be particulate or whisker. The particulates metal matrix composite are in particular interest due to their lower cost and isotropic properties. The properties of metal matrix composites control by volume fraction and size of the reinforcement as well as their interface. When the reinforcement distributed uniformly around the matrix an optimum set of mechanical property like specific strength, specific stiffness, abrasion resistance thermal conductivity and dimensional stability can be achieved [2]. Powder metallurgy route is one of the modern technology for production of metal matrix composites. The main advantage of composite material is low cost. The properties of the composite material mainly define by the property of the reinforcement. The objective of the manufacturing of metal matrix composite is to improve the properties of material like hardness, compressive strength, tensile strength, creep resistance, wear resistance, thermal shock resistance and corrosion resistance. The reinforcement of the composite also helps in improve the physical properties of the material. The particulate metal matrix composite is mainly used for tribological application for its excellent wear resistance during sliding. Self-lubricating properties encounters at high temperature, that’s why gasses and oil can’t be used. So there is a need of excellent solid lubricant which works in a wide range of temperature [3].

Copper powder has been used as industrial and functional metal since last many years. Due to its low strength and high electrical conductivity Cu matrix composites has been develops to get the superior properties in many electrical application. For electrical contact and thermal and electronic packing applications Cu based metal matrix composites is used as it possesses high thermal and electrical conductivity, good corrosion resistance and high melting point

[4]. Pure copper is used in electrical and electronics industries because of their outstanding electrical conductivity (5.96×10^7S/m), thermal conductivity (401 W/m K). For large scale electrical machinery it is difficult to achieve the transfer of current from one material to other by sliding contact on the surface. This type of contact required high contact force while we need low contact force to reduce the wear of the material.

Carbon fibre reinforced Cu based metal matrix composite are good heat sink material in electronic module. It serves to dissipate heat generated during the operation of current electronic system which contain a high concentration of microchips and powerful parts. Cu is one of the best electrical conductive element and some pith coke based carbon fibres has even high thermal conductivity. The co-efficient of thermal expansion in many application should be in same range as those of the other electrical and electronic part [5].

In Cu-graphite-SiC hybrid metal matrix composites, graphite helps in improving the wear resistance as it acts as a lubricating film on the contact surface and its having low co-efficient of thermal expansion. SiC helps to improve high temperature mechanical properties, wear resistance and hardness of the material. As SiC is semiconducting in nature there is no much reduction of electrical conductivity, so it used in made of electrical conductor and has application in resistance heating flame igniter and electronics components. Copper-graphite-SiC hybrid metal matrix composites mainly used in thermal and electrical packing because of its high thermal and electrical conductivity. Cu based metal matrix used as contact bushes and bearing materials for many electrical contact application. Also this metal matrix composite used as heat sink and packing of many microelectronic compact because of its low co-efficient of thermal expansion.

1.2 Aim and objective of the research work

- Fabrication of Cu-graphite-SiC hybrid metal matrix composite by powder metallurgy route by taking copper, graphite and SiC as the starting materials.
- Improvement of mechanical properties of the composite by taking different composition of Cu, graphite and SiC
- To evaluate the effect of SiC particle size on the mechanical and physical properties of the composite.
- Microstructural characterization and study the interface between Cu, graphite and SiC by scanning electron microscope (SEM) and field emission scanning electron microscope (FESEM).

- To improve the wear resistance and analyse the wear mechanism of different Cu-graphite-SiC MMCs.
- Investigation of deformation behaviour of Cu-graphite-SiC MMCs by compression test.
- Study and optimize the electrical conductivity with improvement of mechanical properties and wear resistance of hybrid composite.

1.3 Scope of the thesis

The thesis comprises of seven chapter. First chapter explain the background, motivation and objective of the research work. Second chapter gives a brief about metal matrix composite and its different fabrication route. This chapter also include the literature review about different Cu-graphite-SiC based metal matrix composite. Third chapter explains the detail experimental procedure and technique adopted. Results and discussion of the present study was elaborately explained in chapter four. Fifth chapter consist of the main findings and conclusions of the experimental works. Sixth chapter presents the scope of future work and seventh chapter shows the different references taken.

Chapter 2

Literature Review

2. Literature review

2.1 Introduction

Composite material is a material system composed of two or more macro constituent with different shape and chemical composition which are insoluble with each other which shows improve properties over the individual materials. Composite materials gives better physical and mechanical properties as compare to mechanical alloy in which the constituent element retains their original properties. Two main constituent of composites are matrix (i.e. metal, ceramic and polymer) and reinforcement which remain separate and distinct within the finished structure. Matrix is the continuous phase which supports the reinforcement material by maintaining their relative position. The reinforcement material embedded into the matrix to get the desirable properties of the composite like wear resistance and thermal conductivity. Typically, reinforcing materials are strong with low densities while the matrix is usually a ductile or tough material. The combination of matrix and reinforcement also depends upon strengthening mechanism. The matrix material is select on the basis of its applications. Composite material generally classify as

i. Metal matrix composite (MMC)
ii. Ceramic matrix composite (CMC)
iii. Polymer matrix composite (PMC)

2.2 Metal matrix composite

A metal matrix composite consist of two or more consistent in which at least one should be metal. The other material may be ceramic or any organic compound. When at least three materials are present then it is called hybrid composite. Metal matrix composites are made by dispersing a reinforcement material in matrix phase. Metal matrix composites are fabricated by different processing route like powder metallurgy, mechanical alloying, spray deposition and various casting process. All this technique are associated with the ceramic reinforced composite which may be either in the form of powder or molten. For conventional metal matrix composite for fabrication of composite reinforcement phase is prepared. The main advantage of metal matrix composite is improved high temperature properties, high strength, low co-efficient of thermal expansion and improve wear and abrasion resistance. When a ceramic or organic compound embedded with the metal the properties of metal matrix composite improved. The microstructural and mechanical properties of the composite also depend on the reinforcement particle shape and size. The main drawback of MMC is to overcome the interfacial reaction between the matrix and reinforcement phase and poor wettability between reinforcement and matrix due to the surface contamination of reinforcement. In metal matrix composites main matrix material used are copper, aluminium, nickel, titanium and iron and the main reinforcing material are carbide, boride, nitride, oxide and there mixture [2]. There are wide range of application of metal matrix composite now a days. The major application of metal matrix composite is in automobile body part like wheel, radiator, casing and transmission shaft. MMCs are also used in many electrical construction, air-craft and marine transport.

2.3 Processing of metal matrix composites

2.3.1 Liquid state processing

In liquid state processing infiltration of particulate or reinforcement is involved in casting and liquid infiltration done by liquid metal. When infiltration of reinforcement occurs, reaction takes place in between the molten metal and reinforcement which degrade the properties of fibers. To control the interfacial reaction and to improve wetting fiber coating are applied prior to infiltration. There are different types of liquid state processing. They are:

i. Infiltration process
ii. Dispersion process
iii. Spray process
iv. In-situ process

2.3.2 Solid state processing

2.3.2.1 Diffusion bonding

Diffusion bonding is the common technique for joining of similar and dissimilar material. In diffusion bonding matrix embedded with reinforcement by diffusion phenomenon at high temperature and pressure. At high temperature the diffusion between the metallic surfaces takes place which leads to bonding between them. The main disadvantage of diffusion bonding is high temperature, high pressure and long processing time. Vacuum hot pressing (VHP) is one of the important diffusion bonding process for fabrication of MMCs. By crucial monitoring of diffusion phenomenon we avoid the growth of any undesirable phase at the interface.

2.3.2.2 Powder metallurgy

This is the most common solid state processing technique which is preferred to fabrication of metal matrix composites. In powder metallurgy process the dispersed reinforcement phase combined with the matrix phase to get the desired properties of the material. To get the uniform distribution between matrix and reinforcement proper blending should be done. Powder metallurgy process involves cold pressing to get the desired shape of the component and hot pressing or sintering to get the good bonding between the particles on fabrication of metal matrix composite. The main advantages of powder metallurgy are fabrication of complex shaped component, economic and use for mass production.

2.4 Basic steps of Powder metallurgy

2.4.1 Powder mixing

Mixing of powders is the most common operation in many industry. The main aim of the mixing machine is to get the homogeneous product using less amount of time and energy. The difficulty arises in the powder mixing when we have to blend the powder of irregular shape and size. Most powders are cohesive in nature, when exposed to humid atmosphere or elevated storage temperature agglomeration spontaneously takes place. The mixing characteristic is mainly influenced by the flow behaviour of the powder. Blending of the powder (especially powders with different densities) may results movement of larger ones upwards and smaller particles downwards. The mechanism of mixing of powder depends on physical and chemical interaction between the particles. The shape variation of powder is the extreme range of irregularity in mixing. Segregation of the particle responsible due to the difference in particle size, density, shape and resilience. Difference in the properties of the powder cause unmixing or mechanical jiggling. Mixing device is generally chose according to the material to mix. V-shape mixture is widely used for industrial application for mixing of powder. The other type powder mixture is Turbula shaker mixture and static mixture. The Turbula shaker mixture gives good results in mixing of powder. Turbula shaker mixture is used for homogeneous mixture of powder having different weight and particle sizes. In Turbula shaker mixture mixing arises according to the Schatz geometric theory by the use of rotation, translation and inversion [6].

2.4.2 Powder Compaction

To get the high density product blended metal powder under goes high pressure by rigid die. In this process high pressure exert upon the die on the top in single die pressing and from both top and bottom in double die pressing via vertically moving punches. Under the application of high pressure the powder particle get squeeze together and interlock between them. A certain amount of cold welding between the powders takes place between the surfaces of the particles. After ejection of the sample from the die the sufficient strength in the sample developed which is called green strength which helps in further handling without damage. A lubricant admixed to powder before compaction to reduce tool wear and facilitate the compaction operation. For both technical and economical reason it is most desirable to achieve the highest possible compact density at lowest possible pressure.

There are different type of powder compaction operation

i. Powder compaction in cylindrical die
ii. Isostatic powder compaction

2.4.3 Sintering of powder compact

Sintering is a process in which compressed metal powder heated in controlled atmosphere in a furnace which transformed in to coherent solid at temperature below melting point. During sintering particle-particle diffusion takes place and they bonded together by transport mechanism by which a porous body acquire certain mechanical strength. Sintering of the composites depends on the various parameter. They are

i. Temperature and time of sintering
ii. Density of the powder compact
iii. Protective atmosphere of sintering furnace
iv. Composition of powder mix
v. Geometrical structure of powder particle

Higher the sintering temperature less the time required to achieve the desire bonding between the powder particles. Sintering temperature and time depends upon the compact powder material. Density of the powder compact enhance by distribution of the powder particles and crystal lattice cause by plastic deformation during compaction. Most metal required protection from oxidation since oxide and other contaminant hindered diffusion bonding and development of adequate property. A reducing atmosphere not only provide protection from oxidation but also can reduce any existing oxide. At a particular sintering condition powder consist of fine particle sintered faster than the coarse particles. But fine powder is more difficult to compact due to inter particle friction. To achieve higher density optimization of powder particle size required.

Initial stage of sintering is characterised by the rapid growth of the inter particle neck. In the intermediate stage the pore structure become smooth and has an interconnected cylindrical nature. Then the grain growth occurs with possible pores isolation and slow sintering rate. Cylindrical pores are unstable and collapses into spherical pores at final stage of sintering and slow densification takes place.

There are two common operative mechanism during sintering. They are:

a. Surface transport mechanism
b. Bulk transport mechanism

There are different types of sintering techniques

2.4.3.1 Conventional sintering

Conventional sintering is the most common sintering process which involve heating of metal compact to form metallurgical bond. Here the green sample heated subsequently at an elevated temperature in a control atmosphere in order to form metallurgical integrity. Different control parameter of conventional sintering process are sintering temperature, time, sintering atmosphere and heating rate. Conventional sintering process takes a long time as compare to other sintering process, but it is a stable processing route with economic incentive. Several attempt has been made by taking different initial powder particle size and temperature to control the grain growth of the material during processing [7]. In conventional sintering material surface initially heated then the heat moving inward. So, there is some temperature gradient from the surface to inside of the component [8].

2.4.3.2 Hot isostatic pressing

Hot isostatic pressing is a thermo mechanical process by which material used the applied gas pressure to achieve high density of the material. Flexible dies are used in hot isostatic pressing with isostatic pressurisation. The primary control parameter are pressure, temperature and time. For commercial application hot isostatic pressing grouped in six categories. They are compaction of metal powder, simultaneous heat treatment of cast part, porosity elimination, post-densification of sintered metal parts, rejuvenation of creep or fatigue induced in the component and joining of materials [9]. Hot isostatic pressing is a process simultaneous application of isostatic pressure and elevated temperature to the work piece. High pressure gas such as Ar and N_2 is used to transfer heat and pressure to the compact giving densification. Temperature upto 2200°C and pressure upto 200MPa is possible with using HIP. The work piece is generally encapsulated in an evacuated capsule of ceramic or glass. The main advantage of HIP over conventional sintering is powder are consolidate at higher density at lower temperature, fabrication of complex shaped sample and to get homogeneous density [10].

2.4.3.3 Spark plasma sintering (SPS)

Spark plasma sintering is used to densify any kind of materials, especially the material which are difficult to sinter by conventional sintering. The main advantage of spark plasma sintering is faster heating rate, shorted dwell time and pulse DC voltage. In SPS apart from joule heating, the pulse DC current effectively discharge at the initial stage. Here the high temperature generated by spark plasma and impact pressure eliminated all the impurities present on the surface of the powder particles which helps in maintain the homogeneous temperature [11]. In spark plasma sintering a conductive die like graphite is used. Mechanical pressure of 20-100 MPa applied along the vertical direction and a pulse electric current of high amperage (0.5-40 KA) and low voltage (4-20V) used in the die. A thermocouple is used to control the sintering temperature which is focus at the outer wall of the die. In spark plasma sintering it require much less time and temperature the conventional sintering [12]. Spark plasma sintering is capable of sintering ceramic powder quickly and at relatively lower temperature as compare to other sintering technique [13].

2.5 Brief overview of fabrication and properties of Cu based MMCs by powder metallurgy route

Efe et al. showed that relative density and hardness of the Cu-SiC composite increases with increase in the particle size of the composite. They also observed that by addition of SiC particle hardness of the composite effectively improve with a minor loss of electrical conductivity [14]. **Samal et al.** observed that by milling the Cu-graphite composite powder, initially size of the powder increases due to the flake formation up to 20 hours of milling and sintering of this powder results to reduction in density and hardness of the composite due to porosity. After 20 hours of milling particle size reduction takes place and powder get strain hardened. Sintering of such powder give high density and hardness. They also noticed that transverse rupture strength of the composite increases upto 5 vol. % graphite then it decreases. Compressive strength of the sample got maximum at 5 vol. % graphite after it reduces due to soft nature of graphite [15]. **Nayak et al.** noticed that wear resistance of Cu based hybrid metal matrix composite increases with increases in graphite content. Due to the combined effect of TiC and graphite, wear loss of the hybrid composite reduces with increase in both the reinforcements. They also observed that with increase in TiC hardness of the hybrid composite increases [16]. **Schubert et al.** coated the SiC powder with Mo by sputtering method to control the interfacial reaction between Cu and SiC which is crucial for manufacture heat sink with high thermal conductivity. They observed that highest thermal conductivities should be possible with diamond reinforced CuCr or CuB matrix composites. Rapid hot pressing method they used to fabricate Cu/diamond composite which gave the thermal conductivity value of 640 W/mK along with coefficient of thermal expansion of 11×10^{-6} K^{-1} [17]. **Moustafa et al.** fabricated Cu-SiC and Cu-Al_2O_3 composite by powder metallurgy route. They fabricated the composite by both coated and uncoated SiC and Al_2O_3. They noticed that densification rate of coated powder is more than those made from of uncoated powder. Higher densification was achieved in coated powder composite due to adhesive force between reinforcement and matrix. They also noticed that the compressive strength of coated powder composite is more as compared to the uncoated one [18]. **Tjong et al.** studied the behaviour of Cu-SiC composite prepares by hot isostatic pressing process. By using pin on disc wear tester they studied the wear behaviour of the composite and noticed that by addition of 20 vol. % SiC in Cu matrix wear resistance is very high as compared to pure copper. This is due to the hard ceramic SiC particle present on the sub surface of the composite [19]. **Gultekin et al.** studied the wear and frictional behaviour of Cu based composite used in brake pad and noticed that applied load is the most important parameter for wear behaviour. Friction coefficient decreases with increase in the applied load and it generally varies from 0.2 to 0.45. They also observed that mostly CuO and carbon form on the worn surface. Some wear scar or groove form on the contact surface at lower load and as the load increases permanent plastic deformation in the material takes place [20]. **Zhang et al.** investigated the wear and frictional behaviour of Al based composite reinforcing with different size of SiC particles. They observed that by taking large SiC particles, frictional and wear behaviour of the composites were better as compared to small SiC particle. They noticed that composite with small SiC particle is not suitable for manufacturing drums and brake rotors. Frictional coefficient decrease with increase in load and speed [21]. **Gewfiel et al.** studied the effect of graphite and SiC in Al based composite by taking different composition of graphite and SiC. They noticed that SiC particle greatly improve the hardness and wear resistance of the composite. By increasing the concentration of graphite there was a decrease in wear rate of the composites which governs with the synergic effect of graphite phase sliding properties and its distribution in the composites [3]. **Berner et al.** studied the interface of Cu-C composite and noticed that by heat treatment of Cu-C composite a thin (approximately 50 nm) layer of interface forms which provide bonding between the reinforcement and matrix. The observed the interface by HRSEM to demonstrate it by molecular dynamics and Monte carlo simulations. As carbon is practically insoluble with copper so strong repulsive interaction of component arises which lead to the formation of numerous effect in the matrix which reflect creation of fine nano-crystalline structure [22]. **Feng et al.** studied the effect of lubricant by warm compaction process by taking two different lubricant polystyrene and zinc stearate. They noticed that by increasing compaction pressure, hardness and density of the composite increased but resistivity and graining weight reduced. By increase in compaction temperature hardness and density initially increases then decreases and resistivity and grain weight is just reversed. They obtain the optimum compaction temperature are (120-140^{o}C) and optimum lubricant concentration is (0.4-0.7 wt. %) [23]. **Chen et al.** studied the tribological effect by reinforcing different composition of graphite and hexagonal boron nitride with copper matrix by hot pressing method. They noticed that with increase in graphite content wear rate decreases significantly. Addition of graphite with a low content of hexagonal boron nitride can stabilize the friction and wear properties of composites. All composites have a high wear rate at low sliding speed as compared to high sliding speed because of formation of uniform and more compact tribological thin film on the surface [24]. **Zhan et al.** fabricated Cu-SiC composite by taking 10 vol. % SiC particles with or without nickel coating by powder metallurgy plus hot extrusion method. They noticed that higher bulk hardness and relative density are achieved for the composite containing nickel coated SiC particle then the uncoated one. Nickel coated SiC particle reinforced composite shows improved mechanical properties and increasing extend of interfacial bonding. The nickel coating SiC particle also helps in increase the wear resistance of the composite [25].

Chapter 3
Experimental Details

3. Experimental details

3.1 Synthesis of Cu-graphite-SiC hybrid metal matrix composite

Synthesis of Cu-graphite-SiC hybrid metal matrix composites were performed by conventional powder metallurgy route to study the individual and combined effect of graphite and SiC and to analyze the microstructural, mechanical and electrical properties of the composite.

Cu-graphite-SiC hybrid MMCs were prepared by reinforcing the copper powder with 1, 3, 5, 10 and 15 vol. % graphite along with 2, 5 and 10 wt. % SiC (average size around 50μm) by powder metallurgy route. Powders were blended in a Turbula shaker mixture for 30 minutes to ensure the uniform distribution and mixing of copper, graphite and SiC powders. The composite powders were then cold compacted by uniaxial pressing. The pressure was applied on the die by mechanically using hydraulic press. Sintering of the compact samples were done in a tubular furnace in argon atmosphere.

One another set of sample was prepared by reinforcing 1 and 5 vol. % of graphite along with 2 and 5 wt. % of fine SiC particle (average size around 5μm) by powder metallurgy route using same compaction and sintering parameter to know the effect of particle size on microstructure, mechanical and electrical properties of the hybrid composite.

Table-1 Different compaction and sintering parameter used

Compaction pressure	**700 MPa**
Relaxation time in compaction	**5 minutes**
Sintering temperature	**900^{o} C**
Sintering atmosphere	**Argon**
Holding time	**1 hour**
Heating rate	**5^{o} C/min**

3.2 Characterization techniques used

3.2.1 X-ray diffraction analysis

X-ray diffraction of the polished samples were carried out by Regaku Ultima IV X-ray diffractometer for phase determination of different Cu-graphite-SiC composites. The diffraction pattern was recorded with scanning range of 20^o-80^o at a rate of 20^o/min with step size of 0.05^o. Cu K_α (λ=1.542A^o) was used as the target material with an accelerating voltage of 20 KV.

3.2.2 Microstructural analysis

3.3.2.1 Optical microscopy

Optical microscopy of different Cu-graphite-SiC hybrid composites were carried out by Carl Zeiss AxioCam ERc5s at different magnification. The composite samples were metallographically polished and etched by using 40:60 (by volume) conc. HNO_3 and distilled water. The images were captured by CCD camera attached with the microscope.

3.3.2.2 Scanning electron microscopy (SEM)

Microstructure of Cu-graphite-SiC hybrid composite was studied under scanning electron microscope (JEOL 6480 LV). Micrographs were taken with an accelerating voltage of 20KV by both secondary electron (SEI) and back scattered electron (BSE) image mode as per the requirement.

To see the bonding between matrix and reinforcement and its interface, a high magnification field emission scanning electron microscope (Nova_nano SEM 450) was employed. Elemental analysis of hybrid composite was carried out by energy dispersive X-ray spectroscopy (EDX). X-ray elemental mapping was done to know the distribution of different element present in the composite.

3.3 Physical property study

3.3.1 Density measurement

Archimedes' principle was used to measure the density of the composites. Some error in the density measurement may come due to the presence of interconnected pores and disconnected pores in the composite. Initially dry weight of the composite was measured. Then the composites were kept in dipping it for 24 hours so that pores will be fill with distilled water. To measure the density of the composite, liquid enters inside the interconnected pores. When the pore is completely removed then dipped weight (weight of the sample inside water) and soaked weight (weight of the sample after complete soak of water) were measured. Finally, density of the composite was calculated according to the following formula. `

$$\text{Experimental density} = \frac{Dry\ weight}{Soaked\ weight - Dipped\ weight} \times Density\ of\ water$$

$$\text{Relative density (\%)} = \frac{Experimental\ density}{Theoretical\ density} \times 100$$

Porosity content in the Cu-graphite-SiC hybrid MMCs was calculated according to the followihg formula.

$$\text{Porosity content (\%)} = (100 - Relative\ density)$$

3.4 Mechanical property study

3.4.1 Hardness measurement

To measure the hardness of the composite Vickers hardness tester (Leco Micro-hardness Tester LM248AT) was used. In Vickers hardness tester a diamond indenter having square base right pyramidal shape is used. The angel between the opposite face of pyramid is 136^{o}. A load of 0.3 kgf was applied for a dwell time of 5 seconds. To get the consistent result minimum five measurements were taken at equivalent position.

3.4.2 Compressive strength study

Composites for compression test were prepared by uniaxial die pressing at compaction pressure of 700MPa and sintered the sample at 900^{o}C for 1 hour in argon atmosphere. The dimension of L/D ratio > 0.8 was maintained. Compression test of the composite was carried out in INSTRON 1195 Series IX (Universal testing machine). Rate of loading on the composite was 1 mm/min and maximum load applied was 100KN.

3.4.3 Wear study

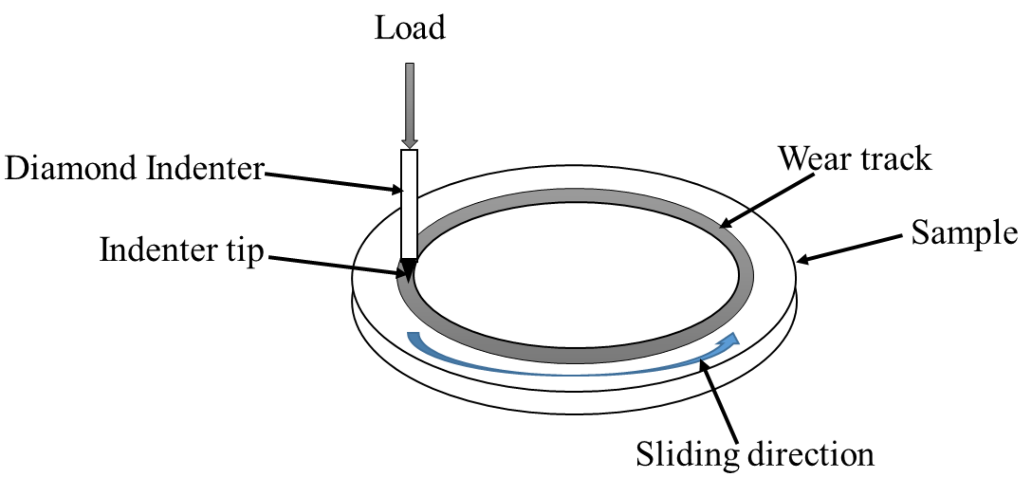


Fig. 1 Geometric configuration of ball on plate wear tester

Wear is the gradual loss of material on the contact surface by the relative motion. Ball-on-plate wear tester (Ducom, TR-208 M1) was used to study non-lubricated sliding wear behaviour of the Cu-graphite-SiC hybrid composites. Geometrical configuration of ball on tester wear tester mechanism is shown in Fig. 1. Diamond indenter rotates at a speed of 20 rpm for 15 minutes against the composite specimens. During the experiment 4 mm track diameter was selected where a constant load of 20N was applied.

3.5 Electrical property study

3.5.1 Electrical conductivity measurement

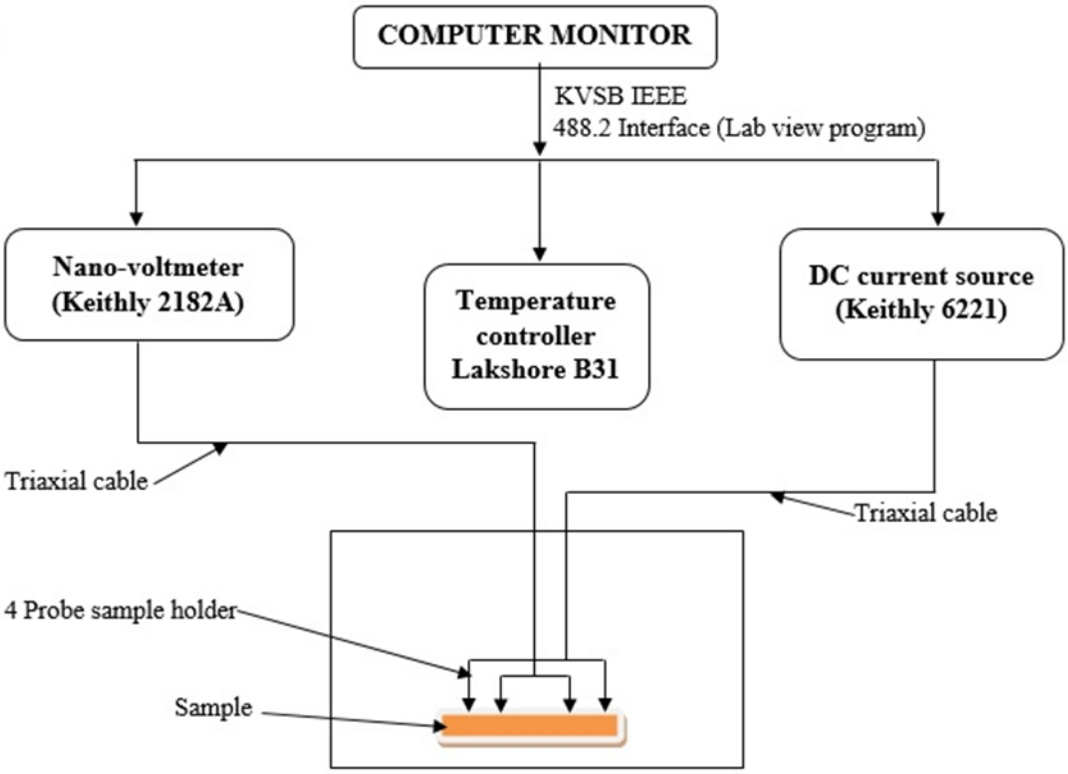


Fig. 2 Schematic diagram of testing system

Electrical conductivity signifies a material's ability to conduct electric current. Electrical conductivity of the composite was calculated by measuring the resistance of the composite. Four probe electrical resistivity measuring instrument was used to measure the resistance of the sample in which two probe connect with the ammeter (Keithly 6221, DC) and another two with the voltmeter (Keithly 2182A). Schematic diagram of the experimental set up is shown in Fig. 2. Resistance of the sample was calculated from the slope of I-V curve which was plotted by using Labview program 488.2 interface.

Electrical conductivity of the composite can be calculated by following formula

$$\sigma = \frac{1}{R} \times \frac{L}{A} \qquad (1)$$

Where σ = Electrical conductivity

R = Resistance of composite

L = Length of the composite

A = Cross-sectional area of composite

Schematic representation of experimental procedure is shown in Fig. 3.

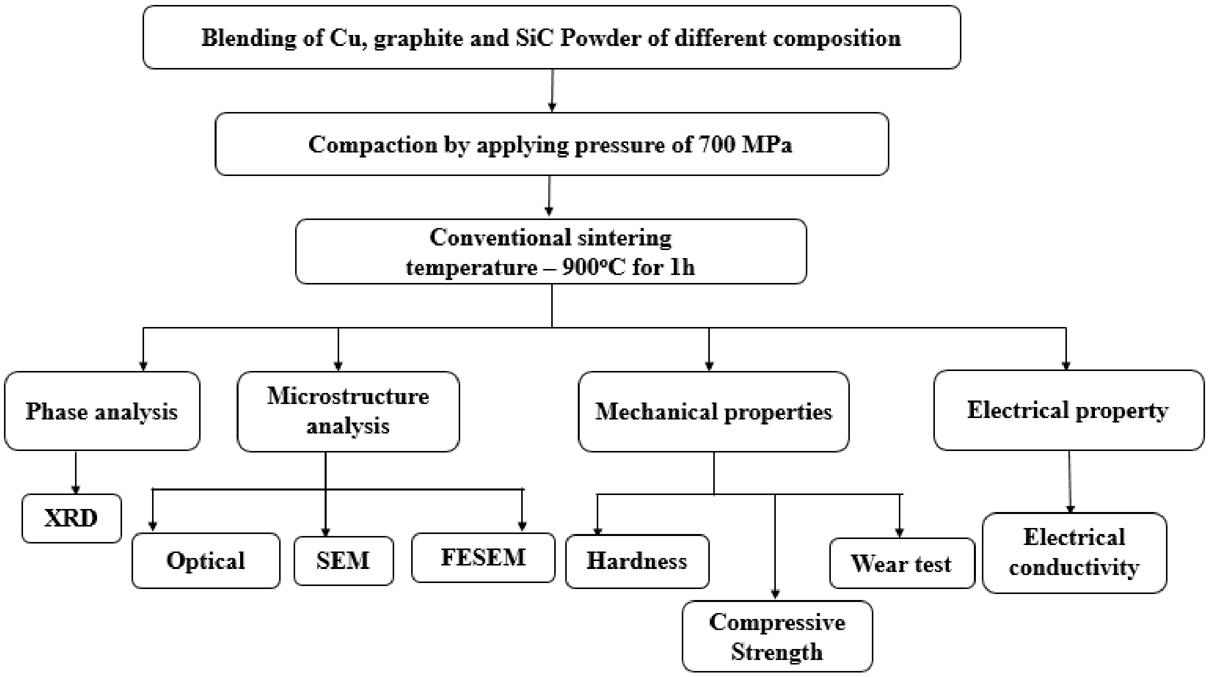


Fig. 3 Schematic diagram of Experimental work

Chapter 4

Results and Discussion

4. Results and discussion

4.1 Characterization of as received powder

In order to manufacture Cu-graphite-SiC hybrid metal matrix composites, starting material Cu (purity 99%, electrolyte grade), graphite (purity 95%) and SiC (purity 95%) with two different particle size were taken. Coarse SiC particle having average size around 50µm and fine having 5µm. Fig. 4 shows the SEM micrographs of as received powder. Fig. 4(a) shows dendritic structure of Cu and (b) graphite having flaky shape. From the micrograph Fig. 4 (c) and (d) we can clearly see the size and angular and irregular shape of SiC particles.

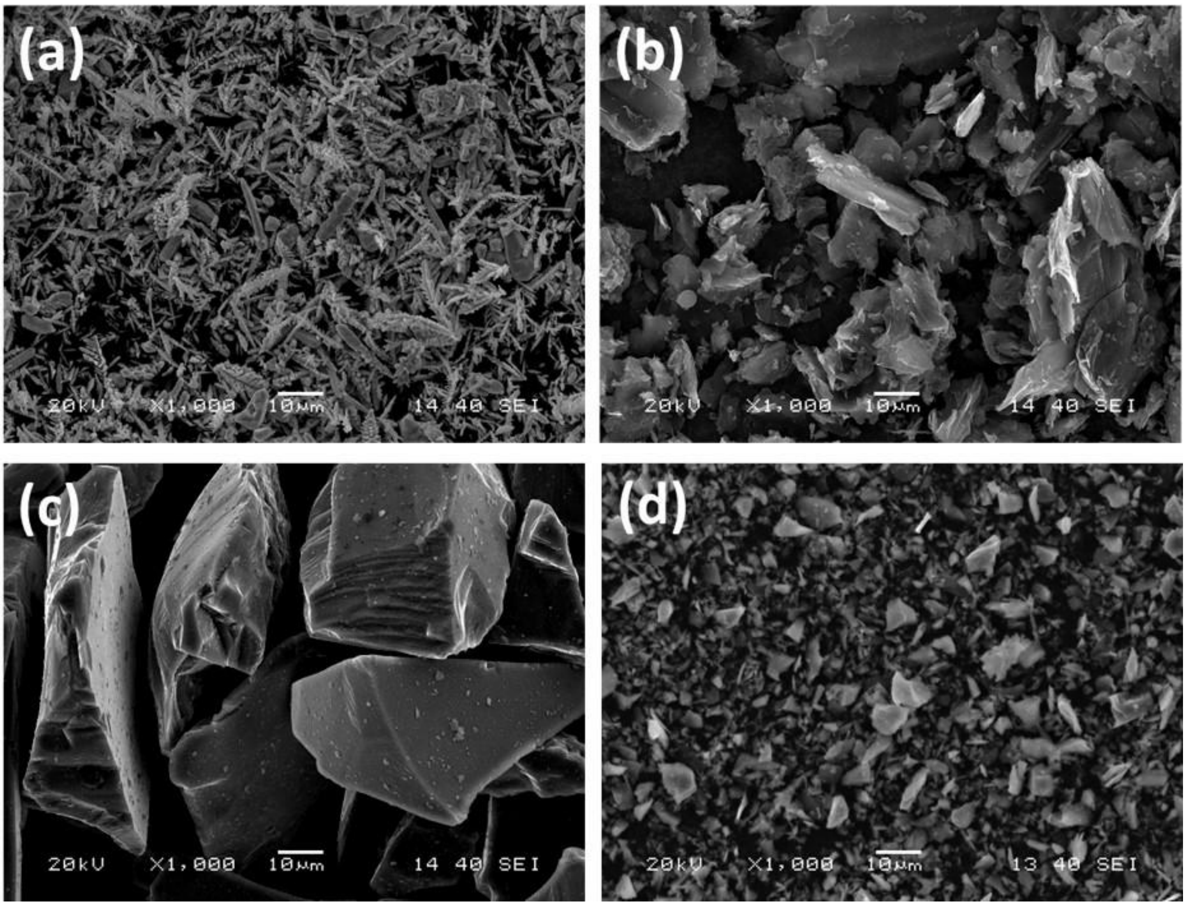


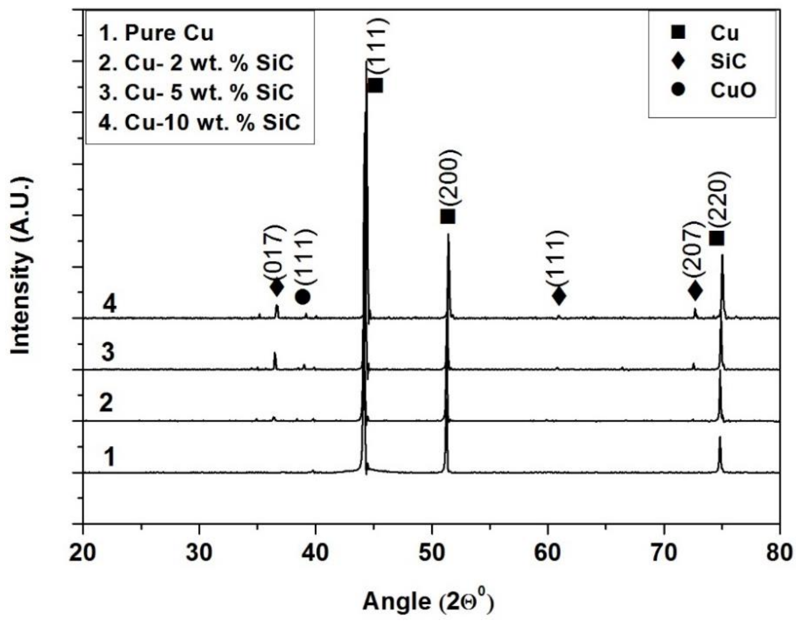
Fig. 4 SEM micrograph of (a) Cu, (b) Graphite, (c) SiC coarse, (d) SiC fine powder

4.2 Characterization of Cu-SiC and Cu-graphite-SiC MMCs

4.2.1 X-ray diffraction analysis

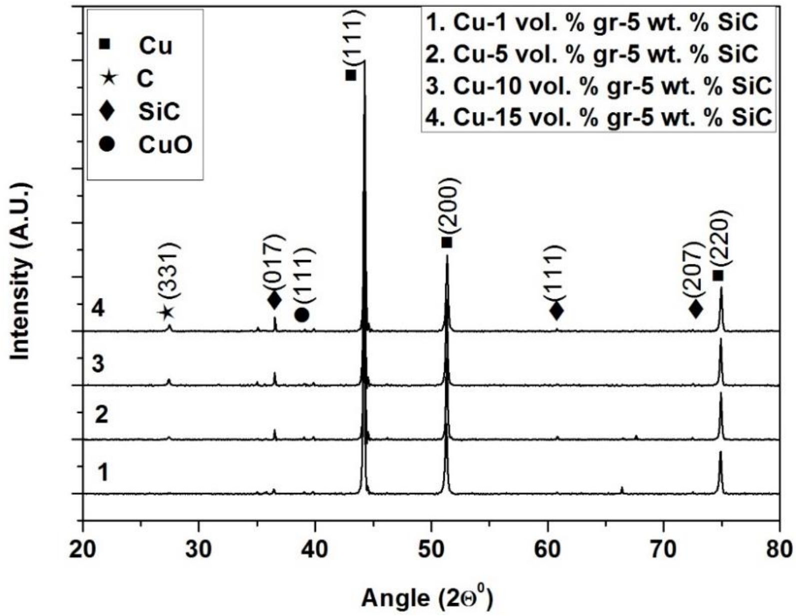
XRD analysis of Cu-graphite-SiC hybrid metal matrix composites with different vol. % of graphite along with different wt. % of SiC was conducted. Fig. 5(a) shows the XRD spectrum of Cu-SiC composite sintered at 900°C for 1 hour with 2, 5 and 10 wt. % SiC. XRD spectrum shows the strong peak of Cu along with some weak SiC and oxide peaks of Cu like CuO. Weak oxide peaks of Cu are present due to the presence of atmospheric oxygen in commercial Ar gas during conventional sintering in tubular furnace. It was confirmed from the XRD spectra that there was no reaction takes place between Cu and SiC.

Fig. 5(b) shows the XRD spectrum of Cu-graphite-SiC hybrid composite containing 1, 5, 10 and 15 vol. % graphite along with 5 wt. % SiC. The XRD spectrum shows the strong peak of copper and very weak peak of graphite and SiC due to their lower content. Also some oxide peaks are present in the spectrum. From the spectrum we noticed that there was no interfacial reaction between Cu matrix with graphite and SiC.



(a)

Fig. 5 XRD spectra of (a) Cu-SiC MMCs



(b)

Fig. 5 XRD spectra of (b) Cu-graphite-SiC MMCs

4.2.2 Optical microstructure study

Fig. 6 shows the optical micrographs of pure Cu and Cu-SiC metal matrix composite and Fig. 7 shows the optical micrograph of Cu-graphite-SiC hybrid composites conventionally sintered at 900^{o}C for 1 hour. From the micrograph we can see that there was uniform distribution of SiC and graphite in the composites and also we observed the irregular SiC particles are uniformly distributed in copper matrix. It was clearly noticed that there is more SiC and graphite particles on the surface at higher content of reinforcement. This may be due to large difference between the density of reinforcement (SiC and graphite) and matrix (Cu) and low solubility of graphite and SiC in copper matrix. So, proper distribution and mixing of graphite and SiC in Cu matrix is a great challenge. It was also noticed that some agglomeration takes place at the higher content of graphite and SiC.

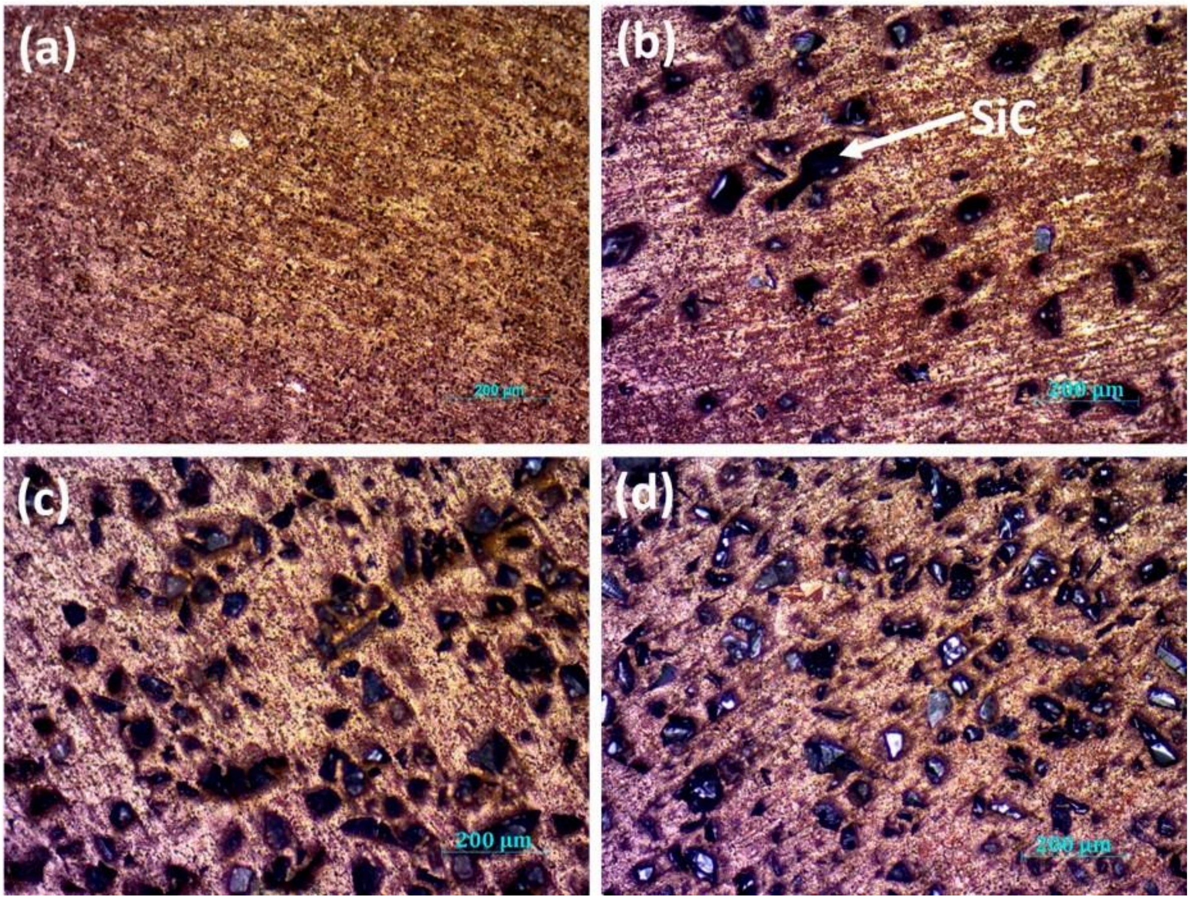


Fig. 6 Optical micrograph of a) Pure Cu, b) Cu-2 wt. %SiC, c) Cu-5 wt. %SiC and d) Cu-10 wt. %SiC

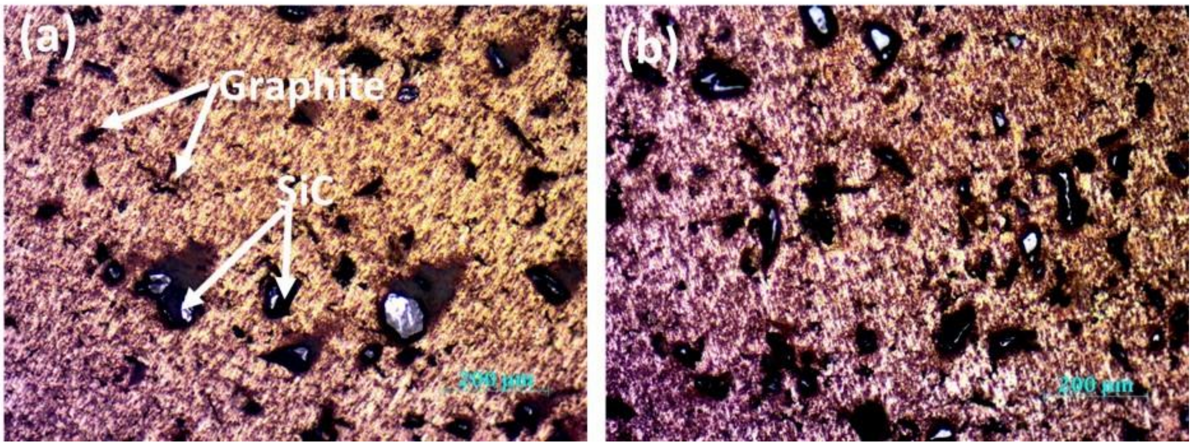


Fig. 7 Optical micrograph of Cu-10 vol. % graphite with (a) 2 wt. %SiC and (b) 5 wt. %SiC

4.2.3 Scanning electron microscopy

Microstructure of the hybrid metal matrix composites were studied under scanning electron microscopy (SEM) and field emission SEM (FESEM) at different magnifications. Fig. 8 shows FESEM micrograph which represents uniform distribution of graphite and SiC in Cu matrix of Cu-5 vol. % graphite-5 wt. % SiC. The SiC and graphite particles are labelled in the micrograph. It was also observed that there is no agglomeration between graphite and SiC.

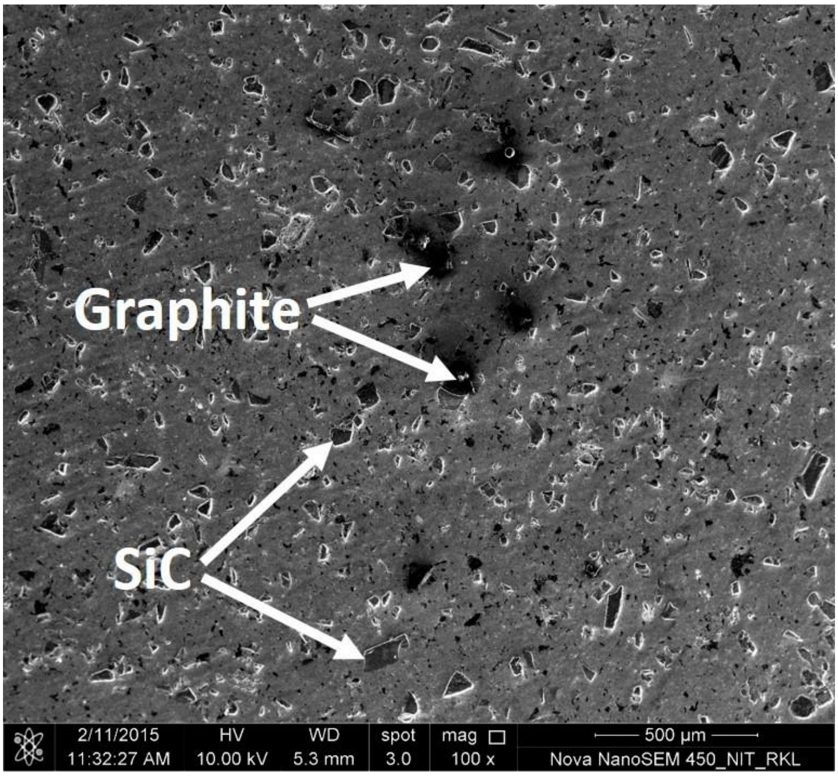


Fig. 8 FESEM micrograph of Cu-5 vol. % graphite-5 wt. % SiC

Fig. 9 shows the SEM micrograph of Cu-5 vol. % graphite-2 wt. % SiC for both coarse and fine SiC powder at different magnification. From the micrograph we can notice the distribution of graphite (black) and SiC (grey) in copper matrix. In the micrographs (Fig. 9a and 9b) coarse SiC particles are visible, whereas in Fig. 9c and 9d fine SiC particles are found. It is also observed that distribution of SiC and graphite are not uniform throughout the matrix due to the large difference in density of matrix and reinforcements.

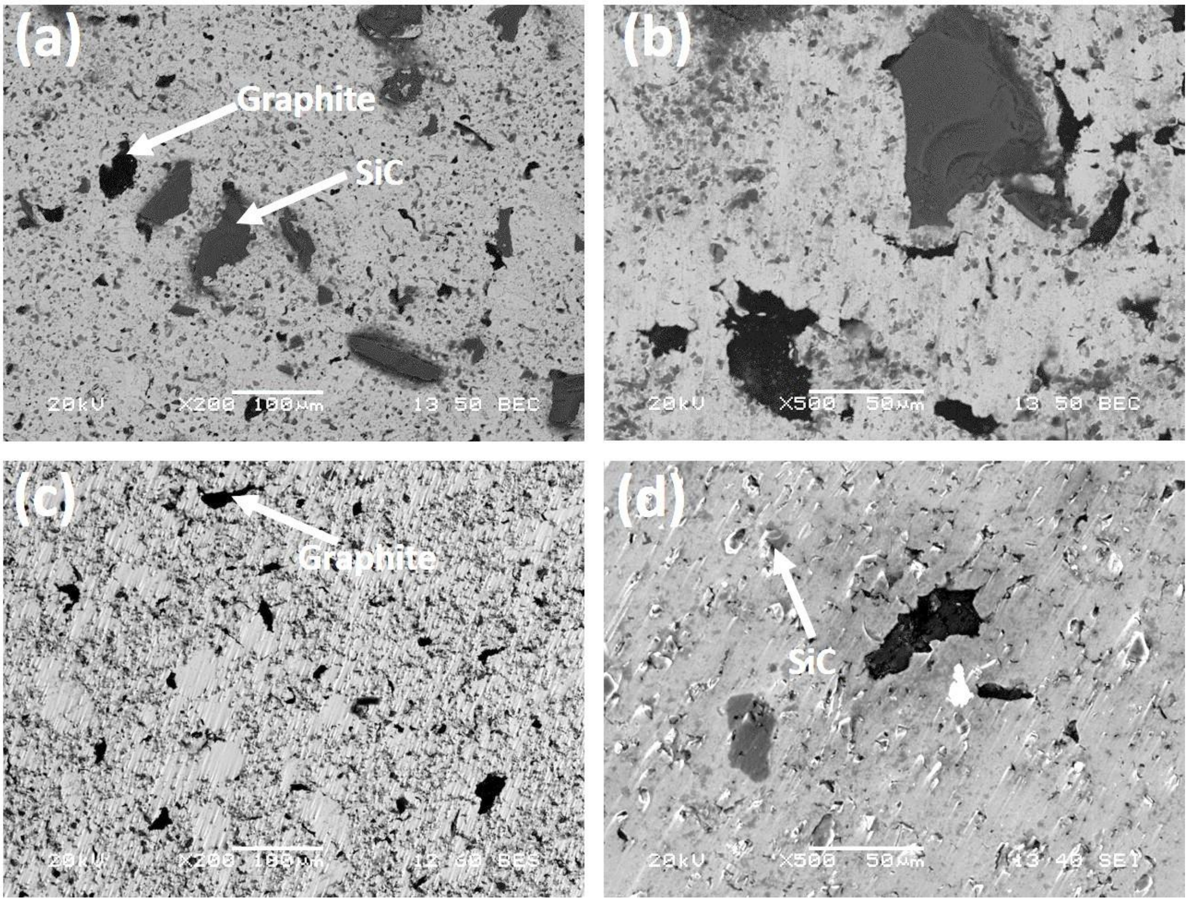


Fig. 9 SEM micrograph of Cu-5 vol. % graphite-2 wt. % SiC (a), (b) Coarse SiC and (c), (d) fine SiC particle

Fig. 10 shows the SEM micrograph of Cu-15 vol. % graphite- 10 wt. % SiC. It is observed that agglomeration takes place at the higher content of graphite and SiC. From the EDX analysis, some oxide peak were noticed that may be due to present of atmospheric oxygen during sintering of the composites.

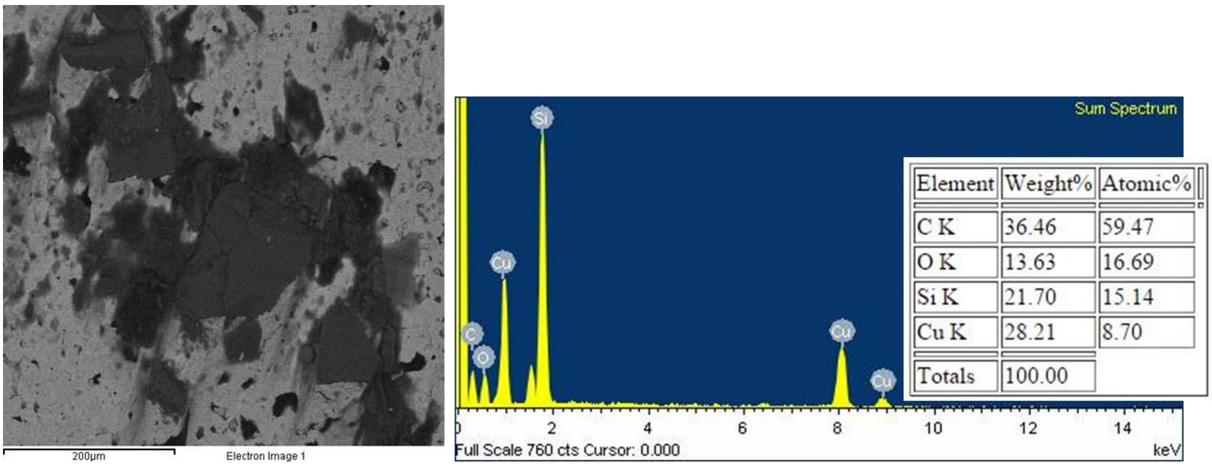


Fig. 10 SEM micrograph and EDX analysis of Cu-15 vol. % graphite-10 wt. % SiC

Fig.11 shows the SEM micrograph and corresponding EDX spectra of Cu-5 vol. % graphite-5 wt. % SiC hybrid metal matrix composite. The micrograph shows that the grey region of the composite is SiC and black region is graphite. The quantitative elemental analysis and also EDS spectra of SiC particle and Cu matrix are shown in the figure.

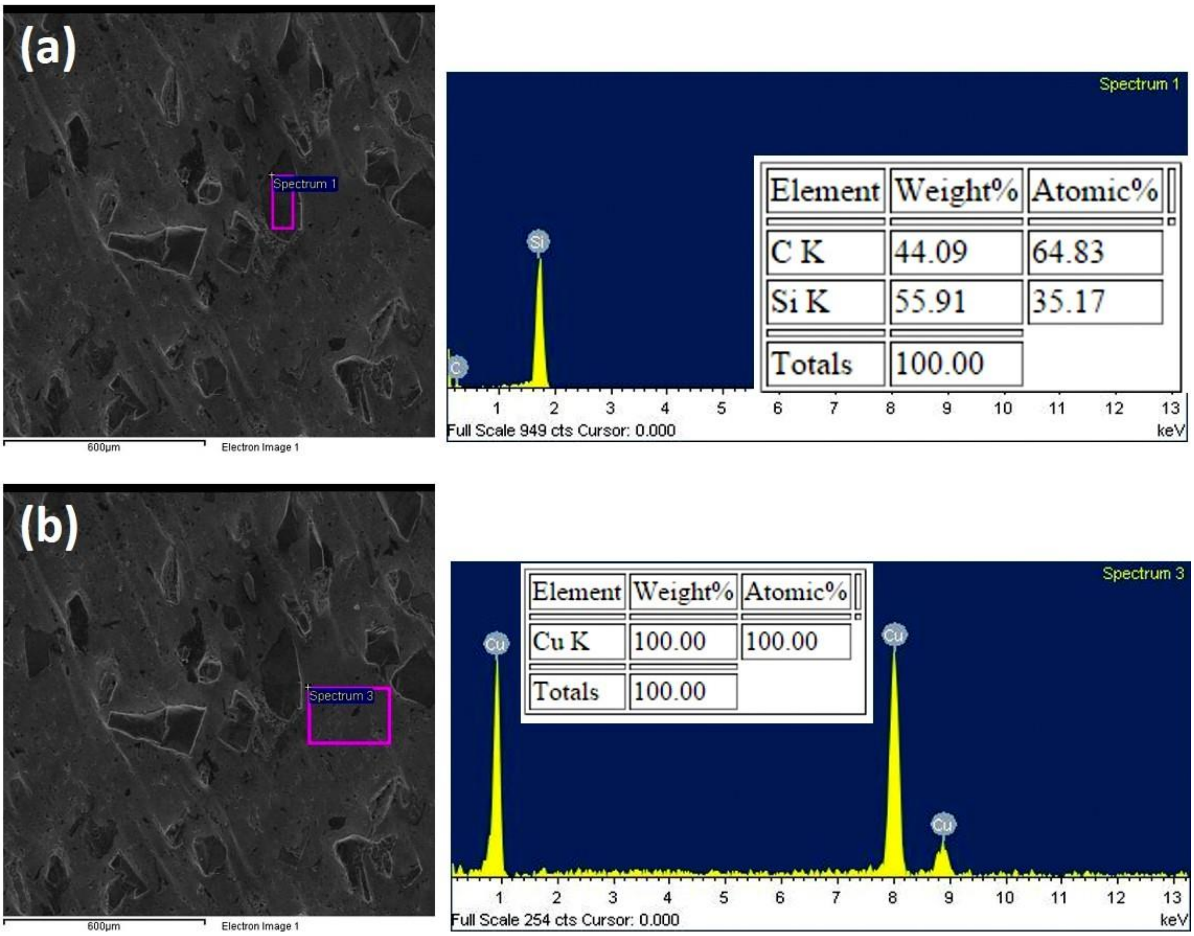


Fig. 11 SEM EDX analysis of Cu-5 vol. % graphite-5 wt. % SiC hybrid composite

Fig. 12 shows the FESEM micrograph of Cu-5 vol. % graphite-5 wt. % SiC composite. The bonding of SiC and graphite particle with copper matrix are clearly shown, where angular and irregular shaped SiC particle and the flaky shaped graphite particles are visible.

Fig. 13 shows the SEM micrograph of Cu-5 vol. % graphite-10 wt. % SiC hybrid composite. From the figure ((Fig. 13a and b) we notice that there is good interfacial bonding between Cu matrix and reinforcements. There is good compatibility between Cu matrix and SiC, graphite reinforcement. From Fig. 13 (c) and (d) it was observed that there was no interfacial product form, which conform that no reaction takes place between reinforcement and matrix during fabrication of composite.

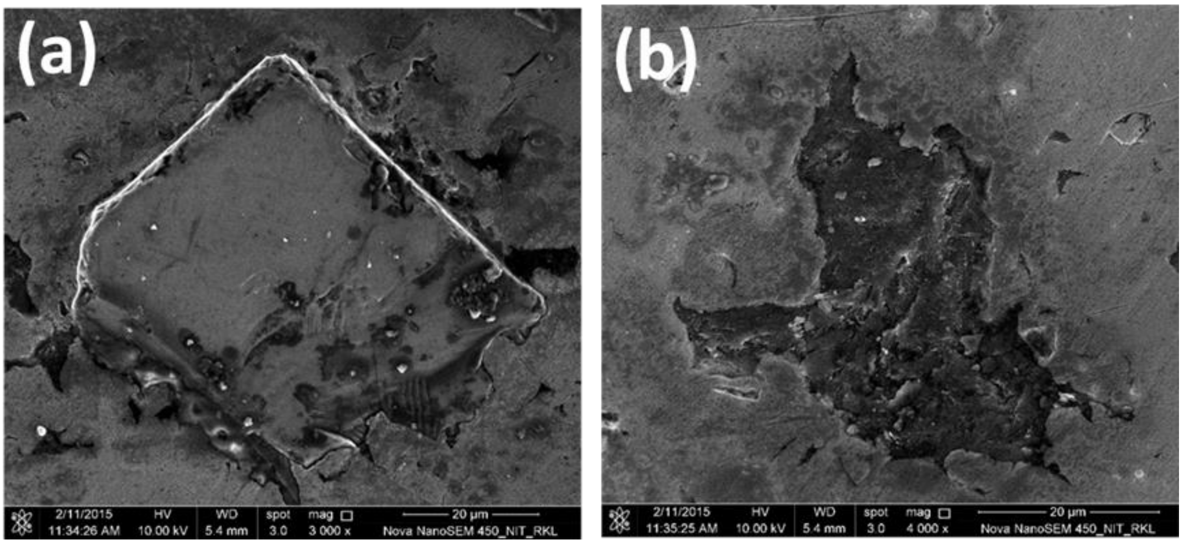


Fig. 12 FESEM micrograph of Cu-5 vol. % graphite-5 wt. % SiC showing bonding of (a) SiC and (b) graphite particle with copper matrix

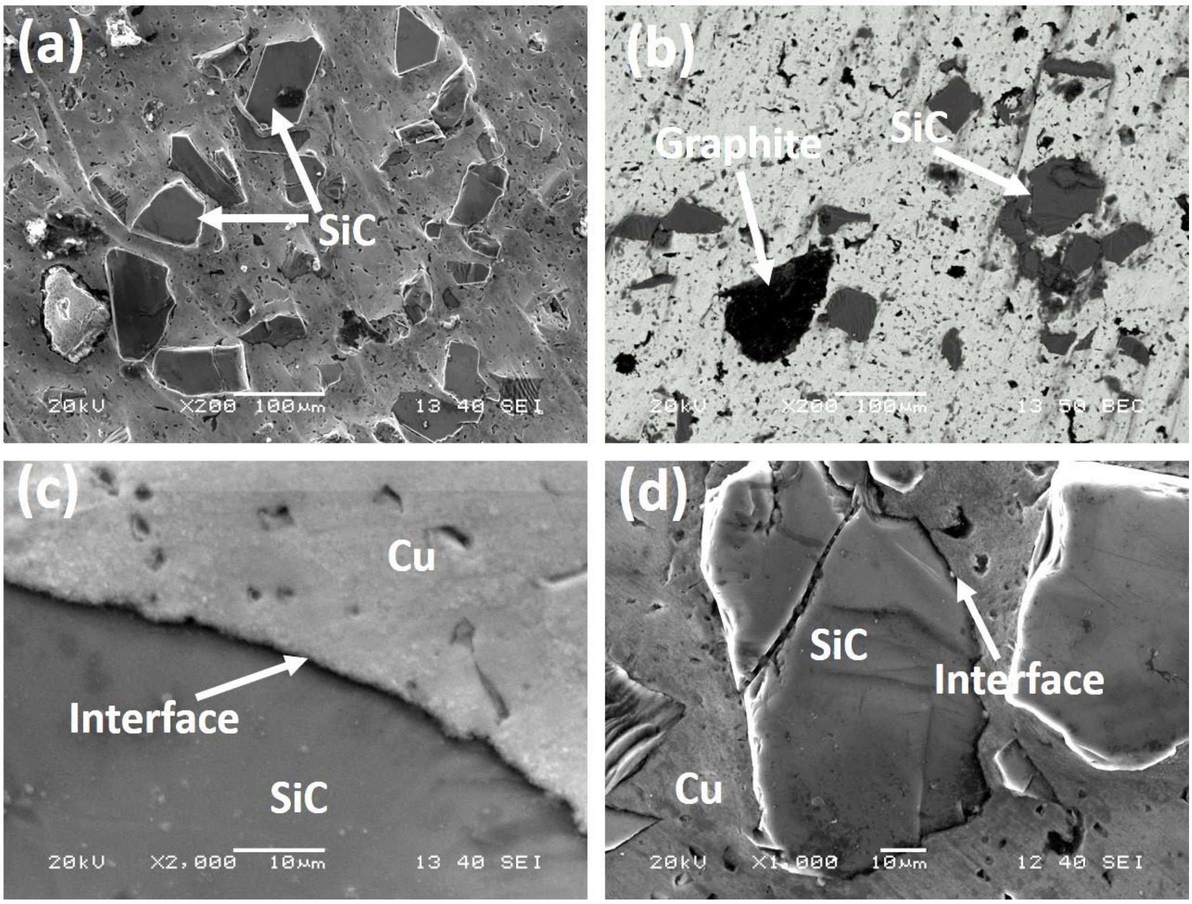


Fig. 13 SEM micrograph of Cu-5 vol. %graphite-10 wt. % SiC (a, b) distribution and (c, d) interface of graphite and SiC particle with Cu matrix

To confirm the presence of different elements in the composites, x-ray elemental mapping was performed for Cu-5 vol. % graphite-5 wt. % SiC composite as shown in Fig. 14. Blue region in the point mapping indicate the Cu matrix phase. Red and green regions show the carbon and silicon respectively. From the mapping we conclude the uniform distribution of reinforcements in the composite.

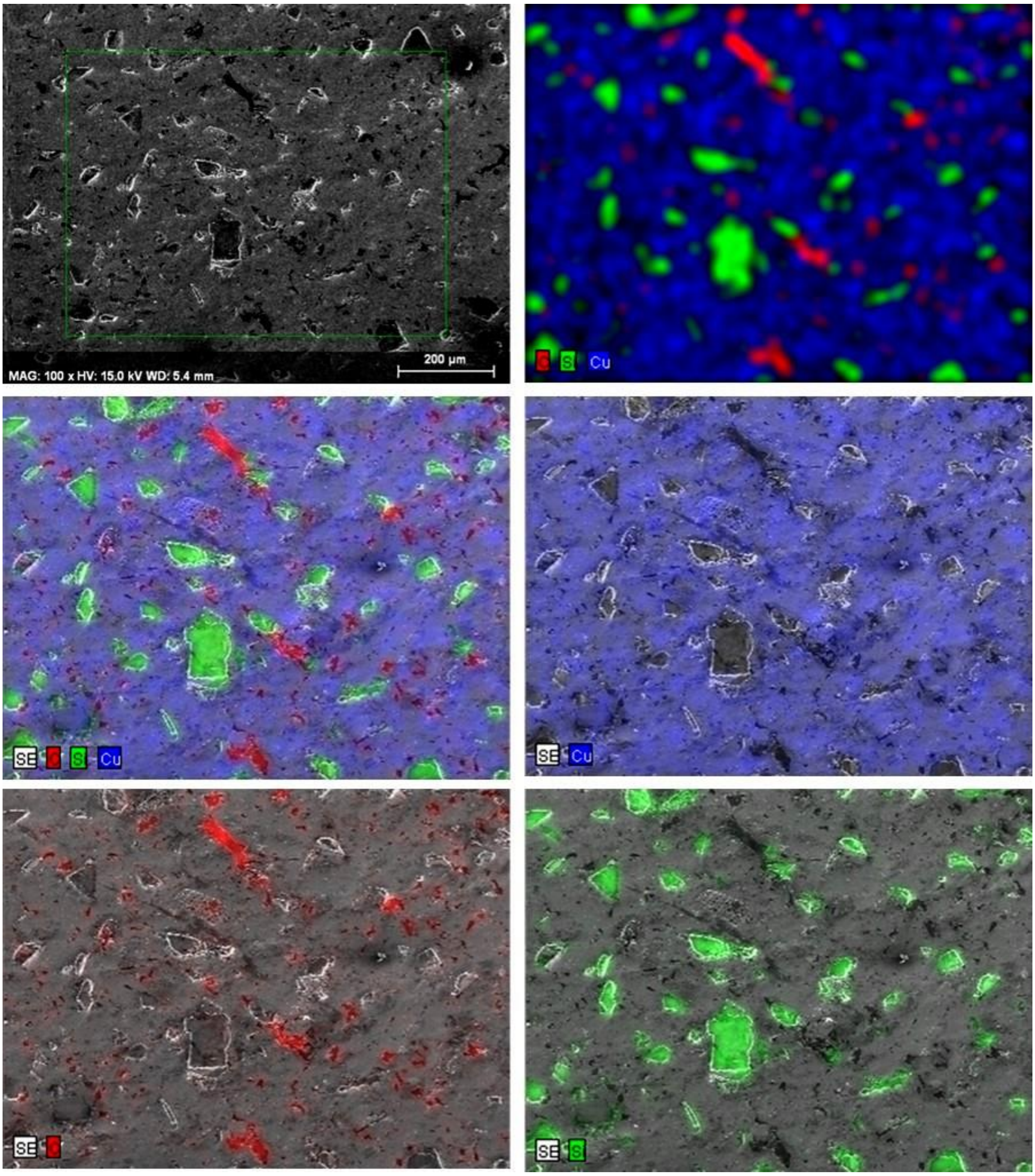
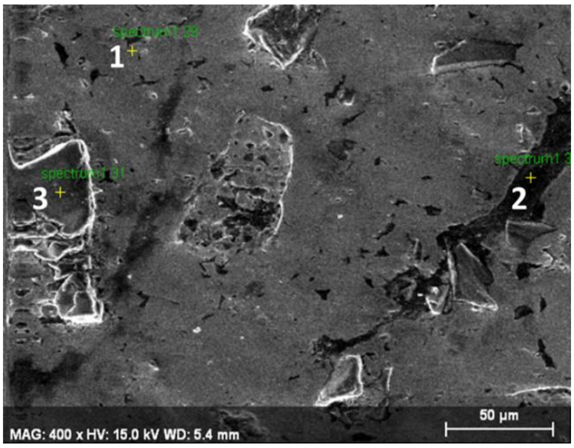


Fig. 14 FESEM micrograph and elemental mapping of Cu-5 vol. % graphite-5 wt. % SiC composite

EDX analysis was carried out for Cu-10 vol. % graphite -5 wt. % SiC composite at three different points. Fig. 15 shows the EDX analysis of the composite where mark 1 denotes the matrix phase (Cu) which contains 100% Cu. Mark 2 denotes graphite particle which contains mainly carbon. However, some SiC particles are mixed with graphite as represented by EDX result. Mark 3 represents the SiC particle which contains both silicon and carbon. The quantitative value of copper, carbon and silicon were shown in Fig.15.



Element / Spectrum	Cu (wt. %)	C (wt. %)	Si (wt. %)	O (wt. %)
1	95.58	4.42	-	-
2	-	91.67	3.20	5.13
3	-	37.38	62.62	-

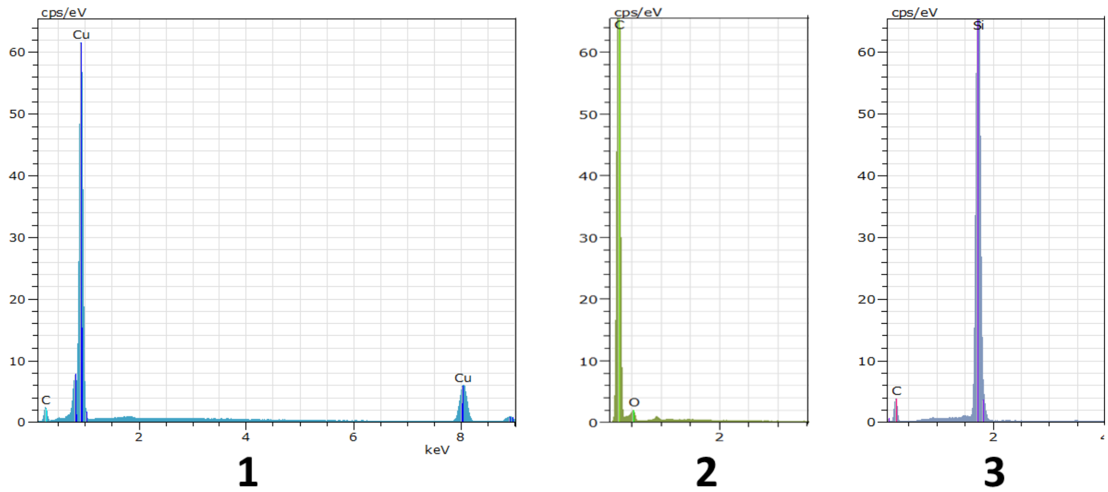


Fig. 15 FESEM EDX analysis of Cu-10 vol. % graphite -5 wt. % SiC at different spectrum

4.3 Physical properties

4.3.1 Density measurement

Fig. 16 shows the variation of relative density with vol. % of graphite for Cu-graphite-SiC hybrid composites containing different amount of SiC. During compaction, graphite particles easily plastically flow as graphite is soft and finally density goes up. It is also observed that the value of relative density increases with increase in SiC content for composites containing coarse SiC. The ceramic particle is hard and non-deformable in nature under the application of pressure but soft particles like Cu and graphite are deformed and act as viscous plastic. Density of a composites depend on size, shape and fraction of matrix and reinforcement. When the fraction of hard particle is low it will well dispersed and deform to fill all the gap and achieve complete densification. Density of the composite also depend on the particle size ratio (i.e. ratio of diameter of soft and hard particle). As the ratio of particle dispersion is much lower than one, higher density can achieve at high fraction of hard particle [26]. As the particle size ratio (i.e. ratio of diameter of soft and hard particle) is more than one for composite containing fine SiC particle, relative density decreases with increase in SiC content.

For composites containing fine SiC, density decreases marginally with increasing graphite. Fine SiC particles are accommodated in the space between Cu and graphite than coarse SiC particles. Hence for the same composition composite containing fine SiC shows higher density than coarse SiC.

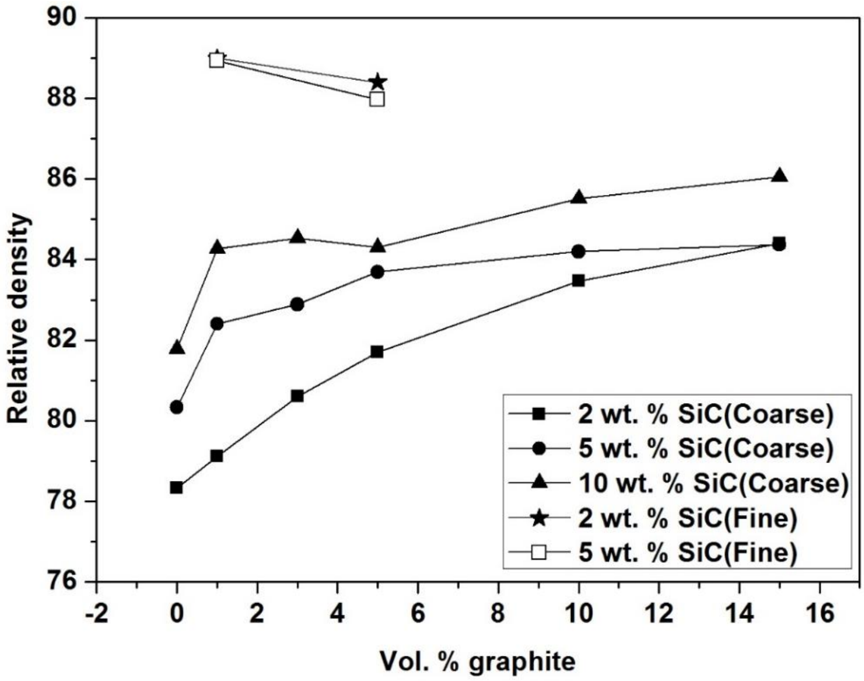


Fig. 16 Variation of relative density with vol. % of graphite

4.3.2 Porosity calculation

Fig. 17 shows the porosity content in the hybrid composite with vol. % of the graphite. Porosity of the composite decreases with increases with the amount of graphite due to soft nature of graphite. The porosity of the hybrid composite decrease with increase with the SiC content in the composite containing coarse SiC particle because of the particle partcle size ratio (i.e. ratio of diameter of soft and hard particle) is much lesser then one. The porosity content in fine SiC particle is less as compare to carse SiC particle as fine SiC particle accommodate tha space between Cu and graphite. As material densify with increase in SiC and graphite content, porosity in the composite decreases.

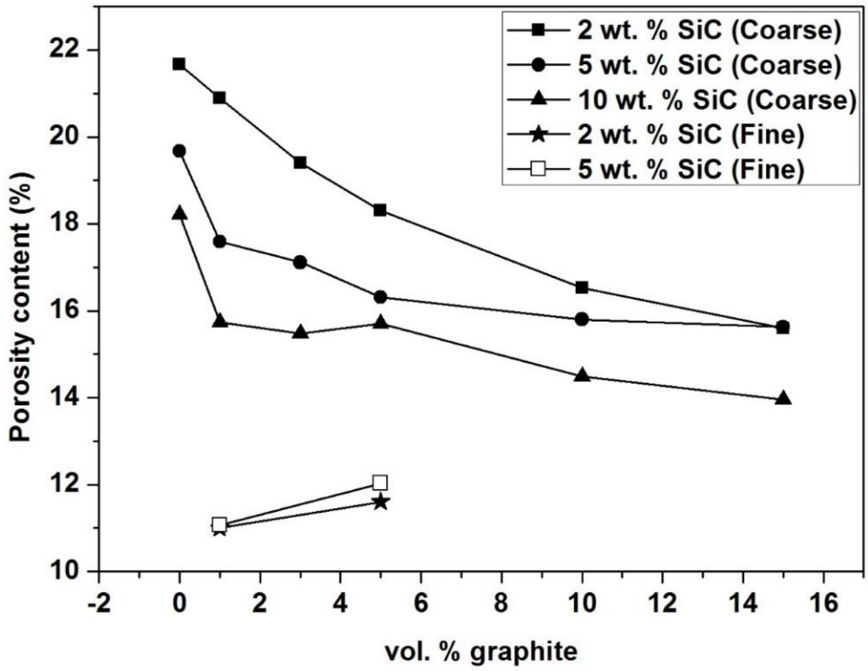


Fig. 17 Variation of Porosity content with vol. % of graphite

4.4 Mechanical properties study

4.4.1 Hardness measurement

Fig. 18 shows the variation of hardness of Cu-graphite-SiC hybrid metal matrix composite with vol. % of graphite for composite containing 2, 5 and 10 wt. % of SiC. Generally hardness of the composite decreases with increase in the percentage of graphite due to its soft nature [15]. For different SiC content the graph has been plotted and it attributes that with increase in SiC content the hardness of the composite increases due to the presence of harder ceramic particle SiC. Maximum hardness value was achieved for higher content of SiC with low content of graphite as the maximum hardness value was 76.1 VHN for Cu-1 vol. % graphite-10 wt. % SiC whereas for pure Cu hardness value was 32 VHN. However, hardness data for some composites were uneven and scattered. Also we observed that hardness of the composite containing fine SiC particle is more as compared to the coarse SiC particle as shown in Fig. 18(a) and (b). For Cu-1 vol. % graphite-2 wt. % SiC we achieve a hardness value of 55 VHN while using coarse SiC particle but hardness value of 58.5 VHN obtained for fine SiC.

As per Orowan hardening mechanism

$$\tau = \frac{Gb}{\lambda} \qquad (2)$$

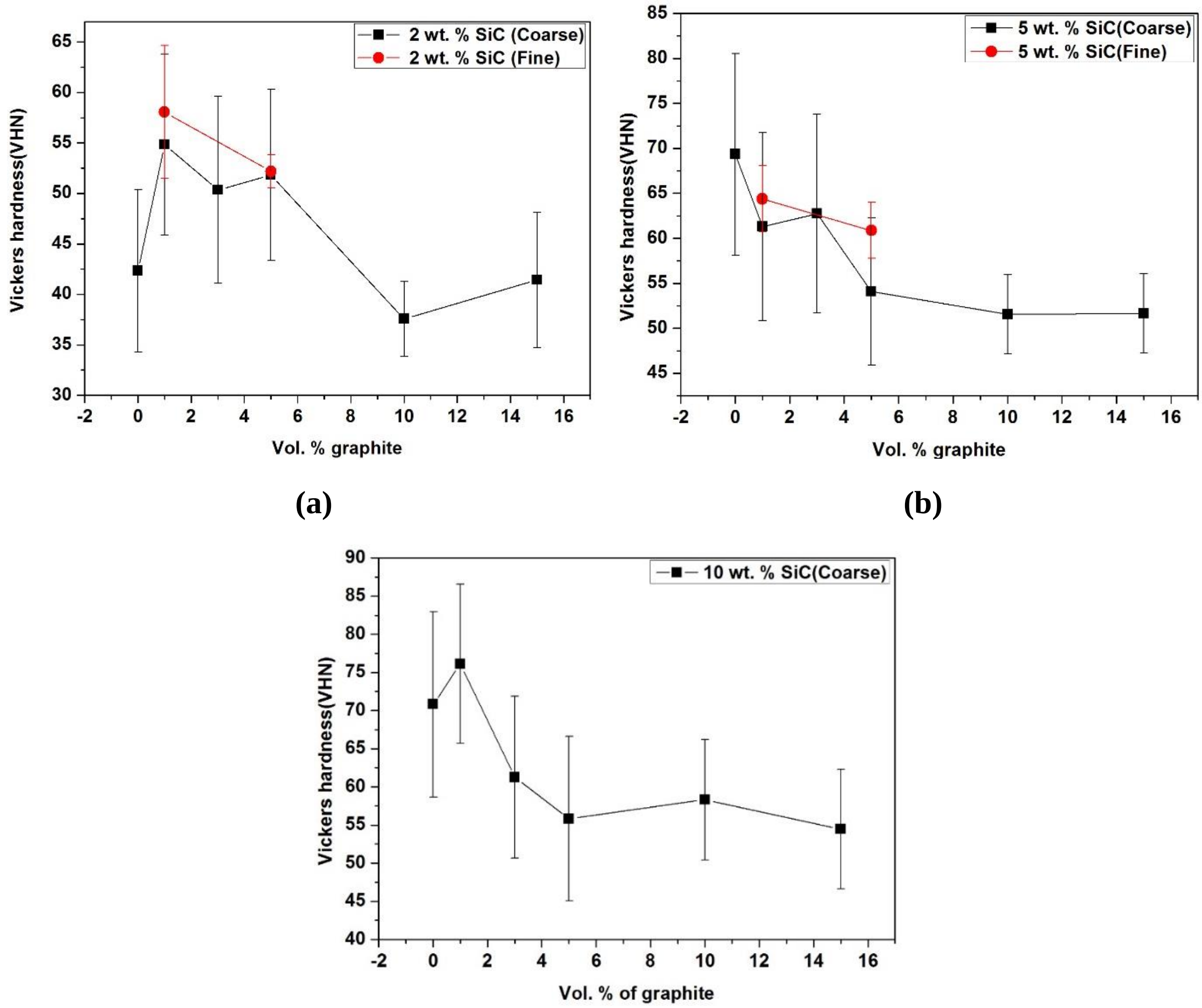
Where τ = Stress

G = Shear modulus

b = Burger vector

λ = Separation between two particles in slip plane

The distance of separation between two particles is less in case of fine SiC particles. Hence more stress is required to dislocate the particles. But distance of separation between coarse SiC particles is more and hence less stress is required for the movement of dislocations. Hence composite containing fine SiC particles exhibit higher hardness than coarse particles.



(a) **(b)**

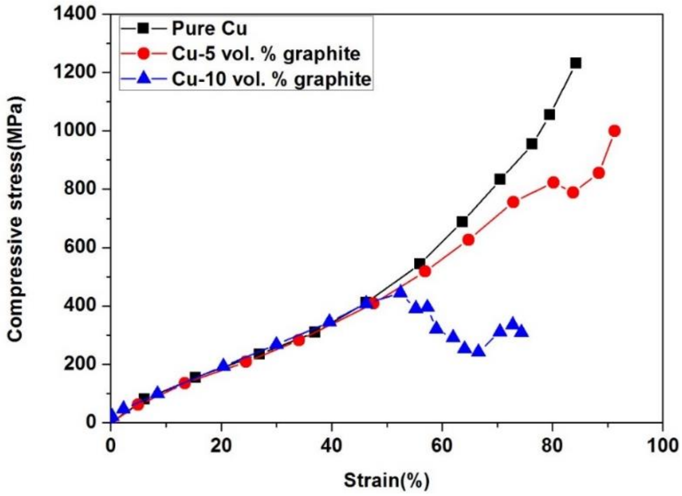
(c)

Fig. 18 Variation of hardness of the hybrid composites with vol. % of graphite for (a) 2, (b) 5, and (c) 10 wt. % SiC

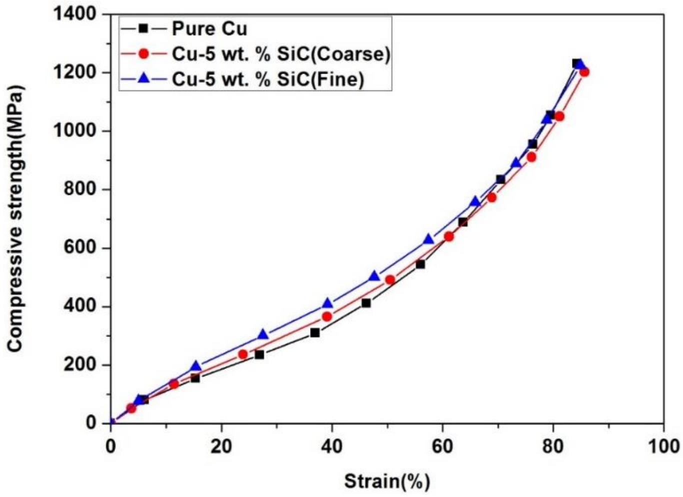
4.4.2 Compressive strength Study

Fig. 19 shows the variation of compressive stress with the strain of the composite. From Fig. 19 (a) by addition of graphite there is reduction in the strength of the composite as graphite is soft in nature. Compressive strength of the composite increases upto 5 vol. % of graphite due to positive dispersion strengthening. It reduces further by addition of graphite, because brittle nature developed due to agglomeration in the composite [15]. For pure copper maximum compressive stress found was 1232 MPa whereas for Cu-10 vol. % graphite the value reduced to 440 MPa. There was no yielding occurs in pure copper due to its ductile property. There was an increase in the strength of the material by adding SiC upto 5 wt. % in Cu-SiC metal matrix composite as shows in Fig. 19 (b). Compressive strength of the composite containing fine SiC particle is more as compared to coarse SiC particles due to improved interfacial strength and higher dispersion strengthening of the particle then the coarse one. There was no yielding occurs in the composite containing upto 5 wt. % of SiC. Further addition of SiC may cause reduction in strength due to brittle nature of SiC.

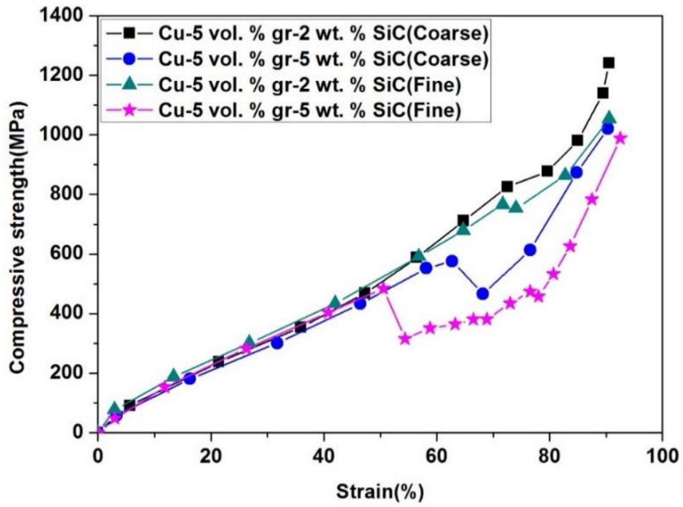
In Cu-graphite-SiC hybrid composite we observed that there was an increase in compressive strength of the material by addition of SiC for fixed content of graphite (Fig. 19c). Compressive strength of hybrid metal matrix composite containing fine SiC particle is more as compared to coarse SiC particle before yielding, but after yielding compressive strength composite containing coarse SiC particle is more than the fine particles. As ductile matrix Cu and graphite particles tend to plastically deform but their deformation is hindered by coarse particle to a large extend then the fine particles. Hence post yielding compressive strength of the composites containing coarse particles are higher than the fine particles. We have achieved maximum compressive strength value of 1240 MPa in Cu-5 vol. % graphite-2 wt. % SiC for composite containing coarse SiC particle whereas 1056 MPa for composite containing fine SiC particle. The yield strength of the composite containing fine SiC particle is less. We have obtained a yield strength of 486 MPa for Cu-5 vol. % graphite-5 wt. % SiC composite containing fine SiC particle whereas 551 MPa for coarse SiC particle.



(a)



(b)



(c)

Fig. 19 Variation of compressive strength with strain of (a) Cu-graphite MMC, (b) Cu-SiC MMC and (c) Cu-graphite-SiC hybrid MMC

Compressive strength of the material mainly depends on two strengthening mechanism. They are dispersion hardening and grain size strengthening. High yield strength of fine dispersion hardened materials are usually explained by Orowan mechanism for the interaction of dislocation with insoluble dispersoids. If the Orowan type mechanism is assumed the increase in yield strength ($\Delta\sigma_d$) due to non-deformable dispersoids can be calculated by following equation.

$$\Delta\sigma_d \text{ (MPa)} = 0.84\left(\frac{2T}{b\lambda}\right) \qquad (3)$$

Where $$\lambda = r\left(\frac{2\pi}{3f}\right)^{1/2} \qquad (4)$$

Where λ mean distance between the dispersoids which was calculated from r the radius and f volume fraction of dispersoids. T and b are line tension and burgers vector respectively. The value of mean distance of separation between the fine dispersoids (λ) is very low in the composite containing fine SiC particle then coarse one. As $\Delta\sigma_d$ value is inversely proportional to 'λ', hence the composites containing fine SiC particles exhibit higher compressive strength [27].

Fig. 20 shows the fracture surface of the Cu-graphite and Cu-graphite-SiC composite. From the figure we noticed that dimple was formed on the Cu rich zone which represents ductile fracture. From the micrograph we can see the de-bonding between matrix and reinforcement and the crack initiation at the interface of the particles. The propagation of crack formed by the weak interface creates failure in the composite under compression. Brittle fracture occurs in Cu-graphite-SiC hybrid composite due to the presence of hard and brittle SiC particles as shown in the figure.

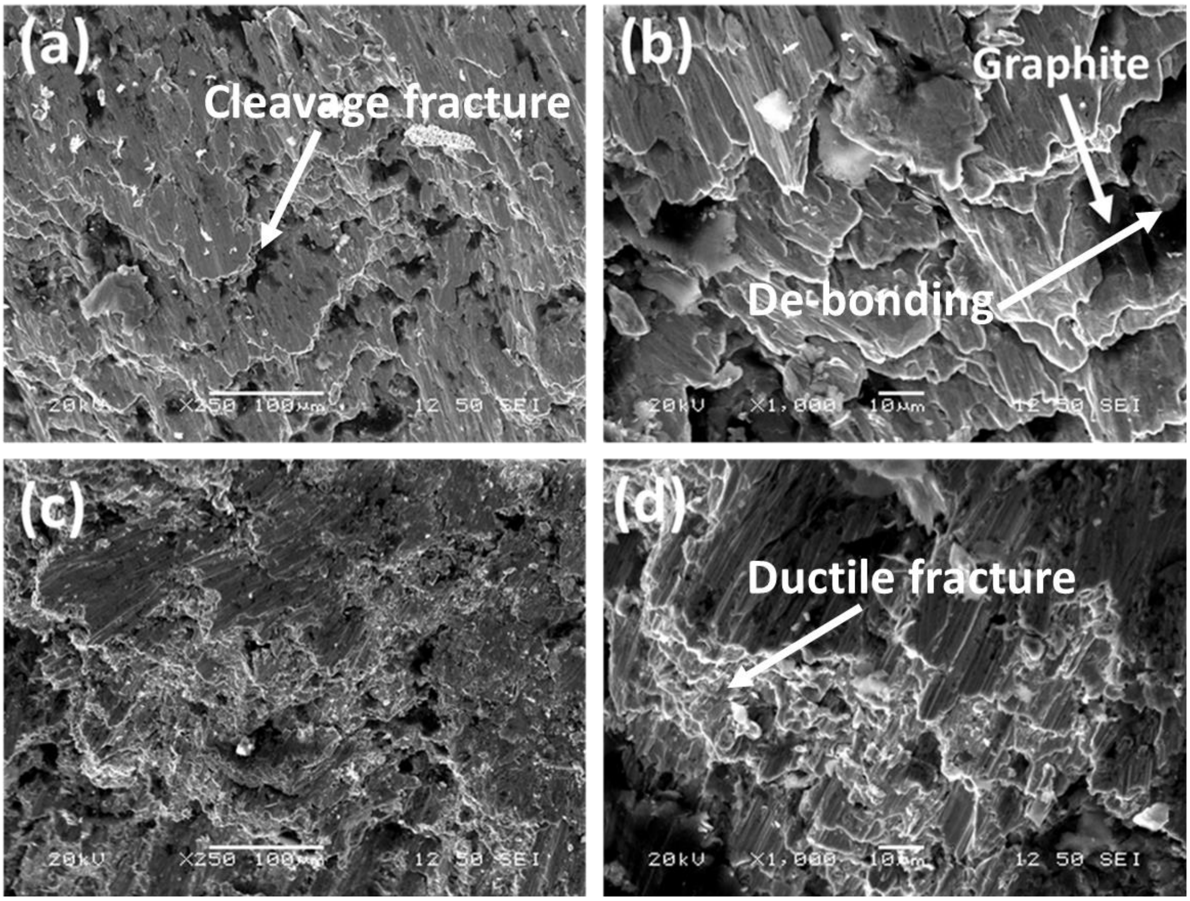


Fig. 20 Fracture surface of (a) and (b) Cu-10 vol. % graphite and (c) and (d) Cu-5 vol. % graphite-5 wt. % SiC

4.4.3 Wear study

4.4.3.1 Effect of graphite and SiC on composite

Fig. 21 shows the variation of wear depth with the sliding distance of Cu-graphite, Cu-SiC and Cu-graphite-SiC composites. From the graph we observed that wear depth of Cu-graphite composite is lower as compared to Cu-SiC composite as graphite acts as a lubricating film on the contact surfaces. By adding 2 wt. % SiC in Cu-graphite metal matrix composite wear depth increases but when we add 5 wt. % SiC in the composite it again decreases. It can be said that optimum amount of graphite and SiC into Cu shows minimum wear depth. SiC particle helps in improving the wear resistance because hard SiC particle support the stress on the contact surfaces and prevent the plastic deformation and abrasion occur, which reduce the worn of the material. The increase in wear resistance is due to strengthening of the composite by fine dispersion of hard ceramic phase SiC in Cu matrix. The bonding between reinforcement and matrix plays also an important role to improve the wear resistance. It can be seen from the graph that there is sudden rise of wear depth which is due sliding of hard SiC particle on contact surface. It is also noticed that wear depth initially increases at very high rate but after sometime it remains almost constant for the composite containing graphite. At the very beginning of wear test there is no lubricating film on the contact surfaces and finally there is a steep rise of wear rate. However, after some time the rise of wear rate is very slow as sliding surfaces are covered by lubricating graphite film. In case of composite containing SiC, wear rate gradually decreases as SiC is hard and brittle and hence abrasion takes place. There is no lubricating film on the contact surfaces.

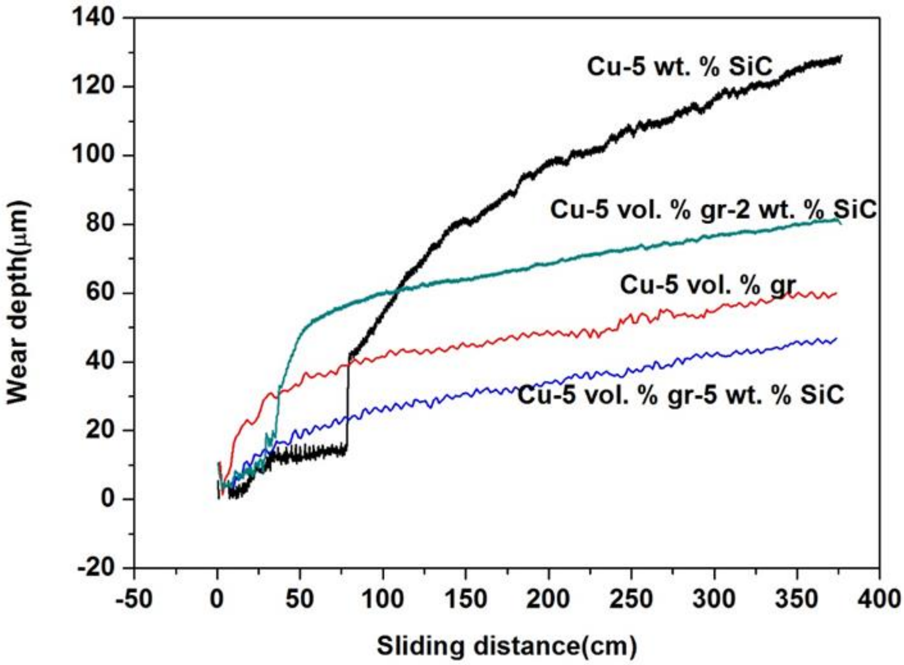


Fig. 21 Variation of wear depth with sliding distance for different composites

Fig. 22 shows the SEM micrographs of worn surface of pure copper and Cu-5 wt. % SiC at a load of 20N and the indenter was rotated at a speed of 20 rpm for 15 minutes. From the micrograph we noticed that more de-lamination occur in pure Cu as compared to Cu-SiC metal matrix composite. Due to the presence of hard and brittle SiC in Cu-SiC composites there is pull-out of SiC from the surface. Deep grooves are visible on the worn surface for Cu-SiC composite. During the wear test the temperature of the contact surface increases due to the rubbing action of brittle SiC particle. The increase in temperature also increases the loss of mass, matrix softening, de-lamination and cracking.

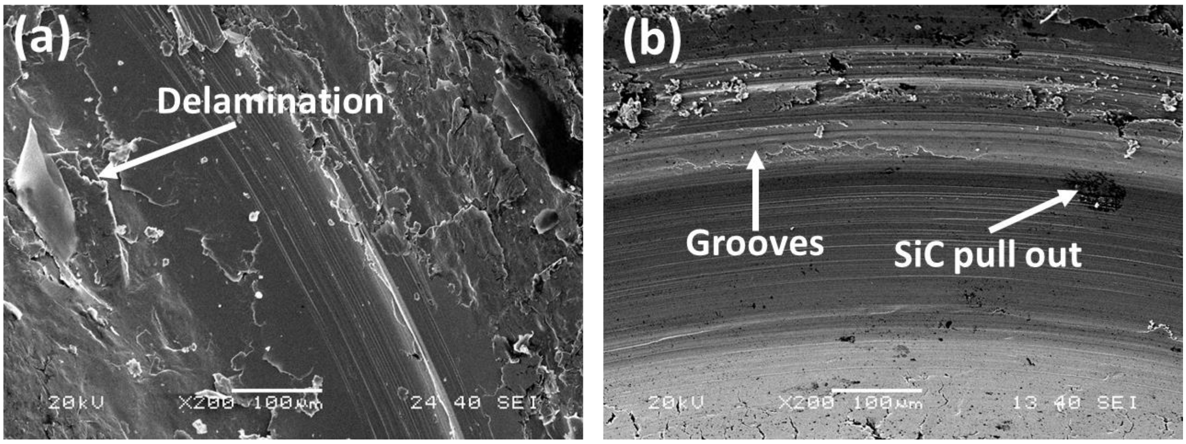


Fig. 22 SEM micrograph of worn surface (a) Pure Cu, (b) Cu-5 wt. % SiC

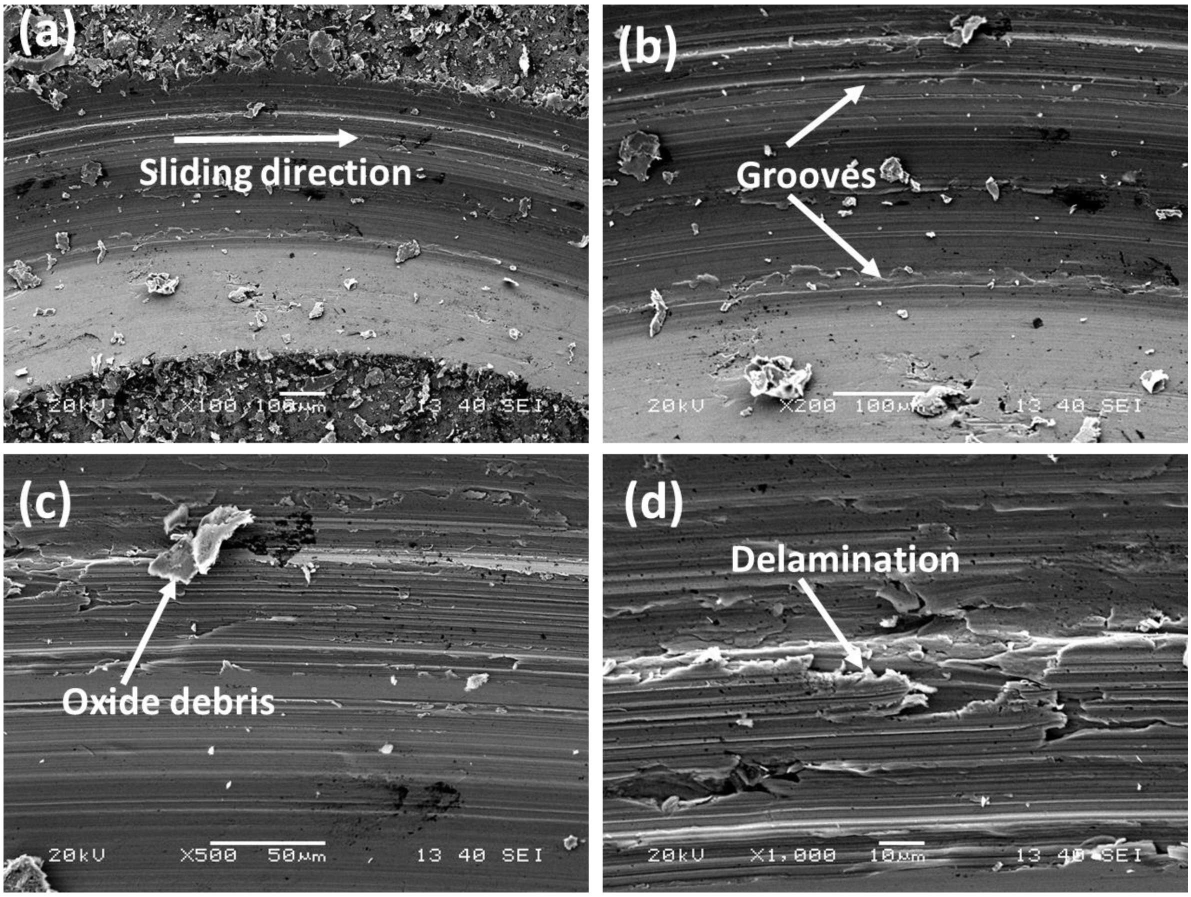


Fig. 23 SEM micrograph of worn surface of Cu-5 vol. % gr-2 wt. % SiC at different magnifications

Fig. 23 shows the SEM images of worn surface of Cu-5 vol. % graphite-2 wt. % SiC at different magnifications. During sliding of composite against diamond indenter, heat is generated and oxidation takes place. Hence oxide debris is visible on the worn surface of the composite. Due to the presence of brittle SiC particle deep scratches are also visible on worn surface (Fig. 23 b &c). Fig. 23 (d) shows te de-lamination occurs on the contact surface at higher magnification. During de-lamination there is peeling of thin layers and flake-like wear debris forms on the worn surface of the hybrid composite. Worn surface is relatively smooth because of presence of graphite on the composite as it acts as a lubricating film on the contact surfaces.

4.4.3.2 Effect of load on composite

Fig. 24 shows the variation of wear depth of the composite with loads of 20N and 40N with sliding speed of 20 rpm for 15 minutes on Cu-5 vol. % graphite-5 wt. % SiC composite. From the graph we noticed that initially wear depth increases very fast after that wear rate decreases with sliding distance. It is seen that wear depth increases with increase of applied load. Frictional force (F) is related with applied normal load (N) and co-efficient of friction (μ) by the equation as:

$$F = \mu N \qquad (5)$$

Higher is the applied load higher will be the frictional force. Wear depth is 100 μm at 40 N load whereas depth is 30 μm at load of 20 N.

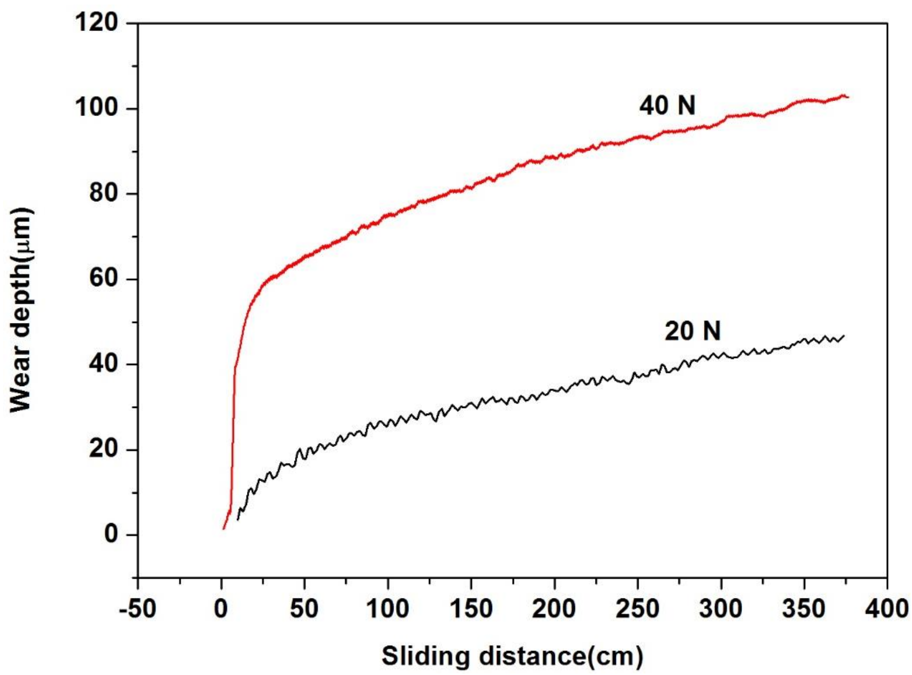


Fig. 24 Variation of wear depth with sliding distance for different loading condition of Cu-5 vol. % graphite-5 wt. % SiC

Fig. 25 shows the SEM micrographs of wear track and worn surface of the hybrid composites at different loading conditions with sliding speed of 20 rpm for 15 minutes. From the figure we noticed that width of wear track is more in 40N load than 20N (Fig. 25a & b). Narrow groove was formed when 20N load was applied and grooves become wide and deep when 40N load was applied. Also from the figure we clearly noticed that de-lamination is more in 40N load as compare 20N (Fig. 25c, d & e, f).

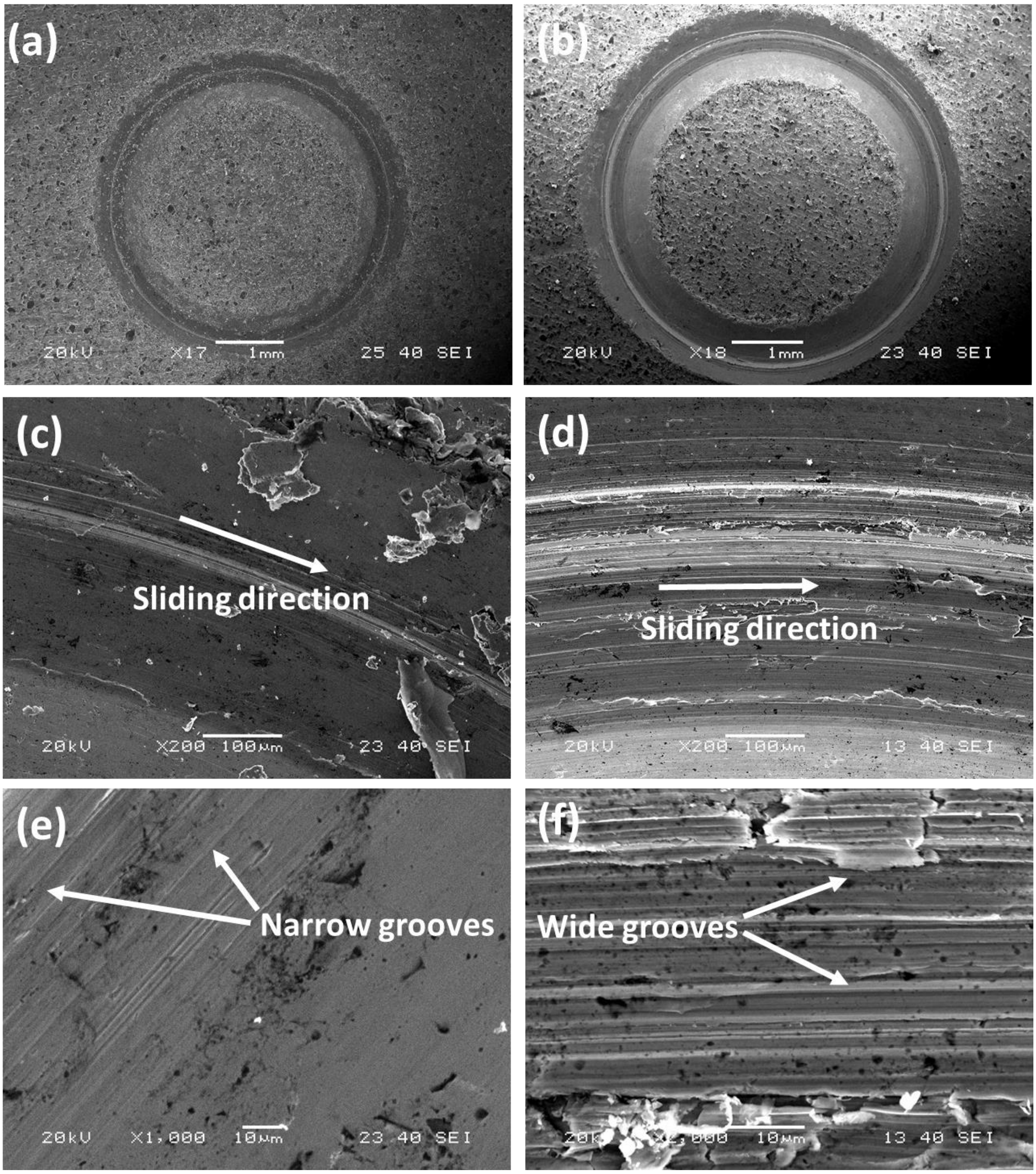


Fig. 25 SEM micrograph of wear track of Cu-5 vol. % gr-5 wt. % SiC when (a, c and e) 20N and (b, d and f) 40N load applied

4.4.3.3 Study of wear debris

Fig. 26(a) and (b) show the wear debris of pure Cu and Cu-3 vol. % graphite-5 wt. % SiC respectively. The size of flake is more in pure Cu due to large amount of plastic deformation as Cu is ductile as compared to Cu-graphite-SiC composite. In case of Cu-graphite-SiC composite, SiC particles are visible along with flake shaped Cu and graphite. Fine SiC particles are generated on the contact surface in the initial stage due to rubbing and micro cutting action of brittle particle. Some fine particle may agglomerate during the wear process. The magnified view of wear debris of pure Cu is also shown in the inset of the picture. From the picture we observed the flake formation by de-lamination.

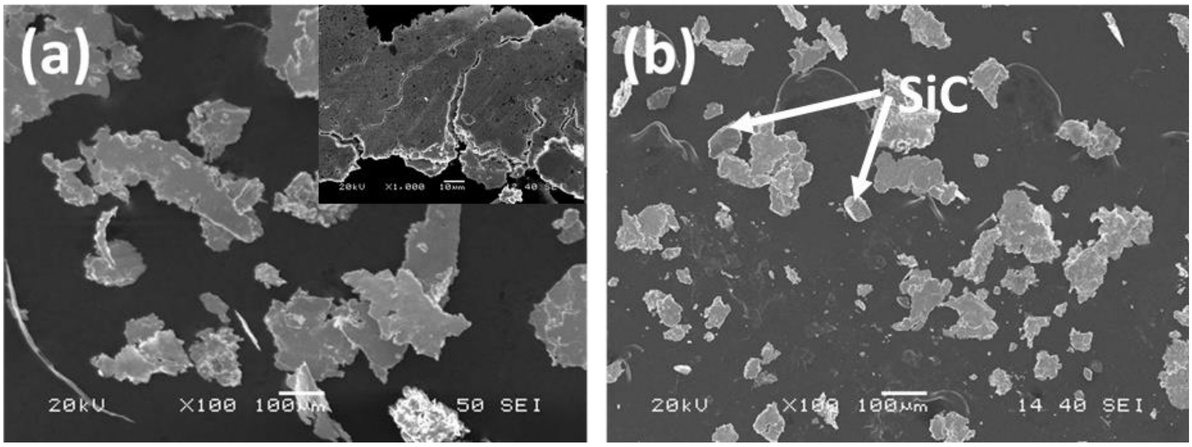


Fig.26 Wear debris of (a) Pure Cu, (b) Cu-3 vol. % graphite-5 wt. % SiC

EDX analysis of wear debris of Cu-5 vol. % gr-5 wt. % SiC is shown in Fig. 27(a). From the EDX analysis we observed the presence of different elements along with formation of oxide in the wear debris. The oxide is formed in the composite due to the heat generated by the rubbing action of the indenter on the contact surface of the composites. Fig. 27(b) show the SEM micrograph of wear debris at high magnification of Cu-5 wt. % SiC which shows the Si particle along with some Cu and oxide content.

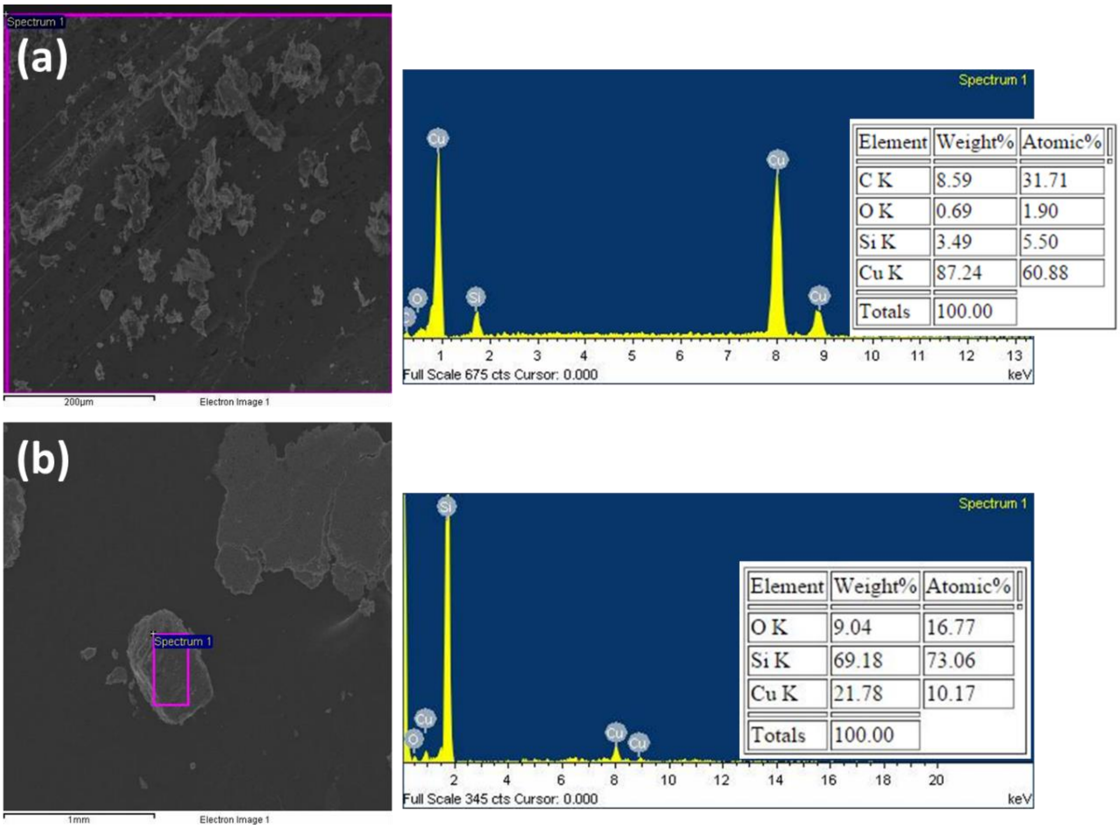


Fig. 27 SEM-EDX analysis of wear debris of (a) Cu-5 vol. % gr-5 wt. % SiC, (b) Cu-5 wt. % SiC

4.5 Electrical property

4.5.1 Electrical conductivity measurement

Fig. 28 shows that electrical conductivity value of hybrid composite decreases with increase in graphite and SiC content because the conductivity of graphite and SiC are lower than that of copper. It is well known that electrical conductivity value mainly depends on the mobility of electrons. SiC is a ceramic material which distort the structure acts as barrier for copper electron and hence conductivity decreases with increase with the amount of SiC.

SiC particle size also affects the electrical conductivity of the composites. Electrical conductivity value increases with increase in particle size as due to addition of coarse particle into copper matrix electron can be scattered easily, as a result conductivity of the composite increases [28].

The electrical conductivity for pure Cu was found to be 4.39×10^6 S/m and it gradually decreases with increase of reinforcement and it reaches to 1.93×10^6 S/m for Cu- 15 vol. % graphite-10 wt. % SiC. Electrical conductivity value was found to be 4.09×10^6 S/m for Cu-1 vol. % graphite-2 wt. % SiC composite containing coarse SiC particles and it decreased to 3.68×10^6 S/m for fine SiC particles.

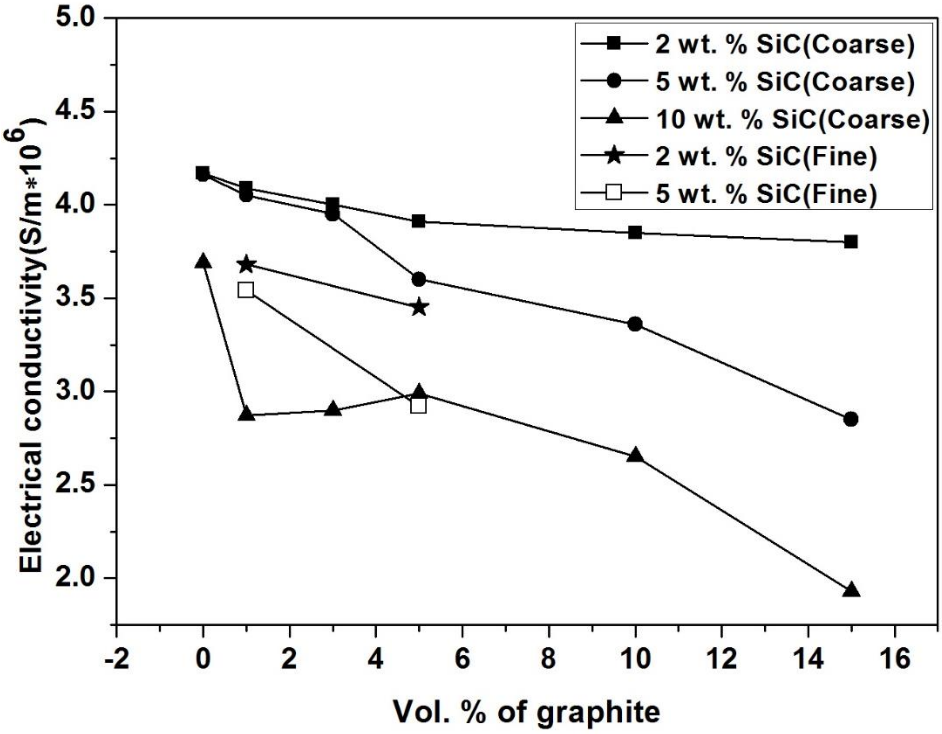


Fig. 28 Variation of Electrical conductivity with vol. % of graphite

Chapter 5

Conclusions

5.Conclusions

The following conclusions can be drawn from the present investigation.

- Cu-graphite-SiC hybrid metal matrix composites were successfully fabricated by using powder metallurgy route taking different composition of graphite and SiC as well as by taking both coarse and fine SiC particle.
- XRD study reveals that there was no reaction takes place between Cu, graphite and SiC during fabrication of composites. However, some oxide peaks are present due to presence of atmospheric oxygen during conventional sintering of the composite.
- Optical and SEM analysis revealed that graphite and SiC reinforcement were distributed homogeneously in Cu matrix. We noticed that there is good bonding between reinforcement and matrix.
- Elemental mapping analysis reveals the uniform and homogeneous distribution of various elements present in the hybrid composites.
- Relative density of the composites increases with increase in both graphite and SiC reinforcement in case of coarse SiC particle. For pure Cu, relative density achieved was 78.0% and it increased to 86.5% for Cu-15 vol. % graphite-10 wt. % SiC in case of coarse SiC. In case of fine SiC, relative density decrease with increase in SiC content. Also higher relative density was achieved in case of fine SiC particle.
- Hardness of the hybrid composite decreases with increase in graphite content and increases with increase in SiC content. Upto 10 wt. % of SiC addition increases the value of hardness to 77 VHN, whereas hardness of pure Cu is 32 VHN. Higher hardness value was achieved using fine SiC particle as compared to coarse SiC particle.
- Compressive strength of the composite decreases with increase in graphite content in the composite. It increases with increase in SiC content in the composite. Compressive strength of the composite containing fine SiC particle is more as compared to coarse SiC particle before yielding. But yield strength of the composite containing fine SiC particle is less when compared with coarse SiC particle.
- Addition of graphite to the composite increase the wear resistance as graphite acts as a lubricating film on the contact surface and by addition of SiC wear resistance increases due to presence of hard ceramic particle. When 40N load applied on the sample wear depth is 102 μm while at 20N applied load wear depth is 46 μm. De-

lamination on the contact surface is more when more load was applied on the composite during wear test.

- Electrical conductivity decreases with increase in SiC and graphite content in the composite. The electrical conductivity value for pure Cu was found to be 4.39×10^6 Siemens/m and it decreases to 1.93×10^6 Siemens/m for Cu-15 vol. % graphite-10 wt. % SiC. By decreasing the SiC particle size the electrical conductivity value decreases.

Chapter 6
Scope for future work

6.Scope for future work

- Cu-graphite-SiC hybrid MMC can be fabricated by advanced consolidation techniques such as hot pressing and spark plasma sintering (SPS).
- Detailed wear study like measurement of co-efficient of friction, wear rate and wear volume can also be studied.
- Interface of the composite can be studied by transmission electron microscopy (TEM).

Chapter 7

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7.References

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